U.S. DEPARTMENT OF COMMERCE
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PB-266 424

Methods for Improvement of Trickling Filter Plant Performance. Part II Chemical Addition

North Carolina Univ at Chapel Hill

Prepared for

Municipal Environmental Research Lab, Cincinnati, Ohio Wastewater Research Div

Jan 77

PB 266 424

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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-77-012

2.

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE
METHODS FOR IMPROVEMENT OF TRICKLING FILTER PLANT PERFORMANCE - PART II - CHEMICAL ADDITION

5. REPORT DATE January 1977 (Issuing Date)

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
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10. PROGRAM ELEMENT NO. 1BC611

11. CONTRACT/GRANT NO.
Contract #14-12-505
Project #11010 DGA

12. SPONSORING AGENCY NAME AND ADDRESS
Municipal Environmental Research Laboratory - Cin., OH
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

13. TYPE OF REPORT AND PERIOD COVERED Final, 1971 - 1972

14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES Studies undertaken on Part I of this project were previously reported in EPA-670/2-73-047a (PB-224 715), "Methods for Improvement of Trickling Filter Plant Performance - Part I - Mechanical and Biological Optima," August 1973.

16. ABSTRACT

An experimental program to explore potential methods for removing phosphorus and generally enhancing trickling filter plant performance was conducted at the Mason Farm Wastewater Treatment Plant, Chapel Hill, North Carolina. Preliminary investigations included jar testing with several coagulants and coagulant aids and pilot studies to determine the effect of the point of alum addition on phosphorus removal.

Follow-up full-scale studies utilized the Chapel Hill high-rate trickling filter plant which consists of two parallel identical main-stream trains. From January 25 through October 6, 1972, alum was added to the influent of one final clarifier. Alum dosage and influent flow rates to the dosed train were varied and phosphorus removal, general plant performance, sludge production, and sludge digestion performance were monitored.

Alum addition effectively removed phosphorus and enhanced overall plant performance. Optimization of alum precipitation will require a flow-paced alum feed system, restriction of average dry weather final settling tank surface loadings to 20.4 m^3/day/m^2 (500 gpd/ft^2), and inclusion of tertiary fine solids removal facilities.

Alum sludge decreased the alkalinity and pH in the primary anaerobic digester and led to liquid/solids separation problems in the secondary digester. Separate facilities may be necessary for handling alum-humus sludge from the final settling tank.

cu m

sq ft

sq m

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Sewage treatment, *Trickling filtration, Clarification, *Chemical removal (sewage treatment), Coagulation, Upgrading, *Aluminum sulfate, Sludge digestion	*Phosphorus removal, *Alum precipitation,	13B

18. DISTRIBUTION STATEMENT Release to Public	**19. SECURITY CLASS** *(This Report)* Unclassified	**21. NO. OF PAGES** 122
	20. SECURITY CLASS *(This page)* Unclassified	**22. PRICE** PC A06 / MF A01

EPA Form 2220-1 (9-73)

☆ U.S. GOVERNMENT PRINTING OFFICE: 1977-757-056/5562 Region No. 5-11

EPA-600/2-77-012
January 1977

METHODS FOR IMPROVEMENT OF TRICKLING FILTER PLANT PERFORMANCE

PART II

CHEMICAL ADDITION

by

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Contract No. 14-12-505
Project No. 11010 DGA

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The studies described herein were undertaken to demonstrate the feasibility of upgrading the overall performance of a typical high-rate trickling filter plant through the addition of liquid aluminum sulfate (alum) to the secondary clarifier. A concomitant benefit of alum addition is phosphorus precipitation. The technology emanating from this project should be thoroughly considered by those charged with the responsibility of upgrading existing or designing new trickling filter facilities.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

An experimental program to explore potential methods for removing phosphorus and generally enhancing trickling filter plant performance was conducted at the Mason Farm Wastewater Treatment Plant, Chapel Hill, North Carolina. Preliminary investigations included characterization of quality and quantity of plant flows, jar testing with several coagulants (lime, alum, and iron salts) and coagulant aids, and pilot studies to determine the effect of the point of alum addition on phosphorus removal in a high-rate trickling filter system.

Follow-up full-scale studies utilized the Chapel Hill high-rate trickling filter plant which consists of two parallel identical trains of main-stream treatment units. From January 25 through October 6, 1972, alum was added to the influent of one final settling tank. During the 18 experimental periods, alum dosage and influent flow rates to the dosed train were varied and phosphorus removal, general plant performance, sludge production, and sludge digestion performance were monitored.

Alum addition effectively removed phosphorus and enhanced overall plant performance. Optimization of alum precipitation will require a flow-paced alum feed system, restriction of average dry weather final settling tank surface loadings to 20.4 $m^3/day/m^2$ (500 gpd/ft^2), and inclusion of tertiary fine solids removal facilities.

Alum sludge decreased the alkalinity and pH in the primary anaerobic digester and led to liquid/solids separation problems in the secondary digester. Separate facilities may be necessary for handling alum-humus sludge from the final settling tank.

This report was submitted in partial fulfillment of Project No. 11010 DGA, Contract No. 14-12-505, by the University of North Carolina under the sponsorship of the U. S. Environmental Protection Agency. Research work conducted during Part II of this project and reported herein covers the general time span of mid-1971 to October 1972. Studies undertaken prior to the Part II chemical addition experiments of this project were previously reported in EPA-670/2-73-047a entitled "Methods for Improvement of Trickling Filter Plant Performance - Part I - Mechanical and Biological Optima," August 1973.

CONTENTS

FOREWORD iii

ABSTRACT iv

FIGURES vi

TABLES ix

ACKNOWLEDGEMENTS xi

SECTION

I INTRODUCTION 1

II CONCLUSIONS 3

III RECOMMENDATION 7

IV PRELIMINARY PHOSPHORUS REMOVAL INVESTIGATIONS 9

Characterization of Plant Influent 9
Jar Tests 13
Pilot Plant Studies of Phosphorus Removal with Alum 44

V ALUM ADDITION TO CHAPEL HILL MAIN PLANT 60

The Chapel Hill Treatment Plant 61
Preparatory Work for Alum Treatment 64
Facilities for Alum Treatment at Chapel Hill 66
Sampling and Analysis 69
Description of Experimental Program and Performance Results 71
Discussion of Results 81

VI REFERENCES 102

APPENDIX A. Abstract of Publication Resulting from Project 104

APPENDIX B. Abstracts of Theses Resulting from Project 105

FIGURES

Number		Page
1	Relationship Between pH and Calcium Hydroxide Dose	18
2	Relationship Between pH and Residual Total Inorganic Phosphate in Various Plant Samples	19
3	Effect of Laboratory Filtration on Residual Total Inorganic Phosphorus as a Function of Calcium Hydroxide Dose and pH Level (0.45μ Filter)	21
4	Effect of Laboratory Filtration on Residual Total Inorganic Phosphorus as a Function of Calcium Hydroxide Dose and pH Level (0.22μ Filter)	22
5	Effect of Cationic Polyelectrolyte (Cat-Floc) Addition on Residual Total Inorganic Phosphorus and Turbidity at a Calcium Hydroxide Dose of 80 mg/l and a pH of 9.3	24
6	Effect of Sodium Fluoride Addition on the Relationship Between pH and Residual Total Inorganic Phosphorus During Lime Precipitation	25
7	Polynomial Regression Models for Phosphorus Removal from Influent as a Function of Alum Dosage	28
8	Polynomial Regression Models for Phosphorus Removal from Primary Effluent with Alum Addition	29
9	Polynomial Regression Models for Phosphorus Removal from Trickling Filter Effluent with Alum Addition	30
10	Polynomial Regression Models for Phosphorus Removal from Secondary Effluent with Alum Addition	31
11	Phosphorus Removal from Plant Influent with Ferric Chloride and Ferric Sulfate Addition	37
12	Phosphorus Removal from Trickling Filter Effluent with Ferric Chloride and Ferric Sulfate Addition	38
13	Removal of Total Suspended Solids and Turbidity from Plant Influent with Ferric Chloride and Ferric Sulfate Addition	39

FIGURES (Continued)

Number		Page
14	Removal of Total Suspended Solids and Turbidity from Trickling Filter Effluent with Ferric Chloride and Ferric Sulfate Addition	40
15	Effect of pH on Fe Capture During Iron Addition for Phosphorus Removal	46
16	Flow Diagram Trickling Filter Pilot Plant for Single-Stage Filtration	50
17	Partial Flow Sheet for Chapel Hill Wastewater Treatment Plant	62
18	Typical Diurnal Variation in Total Phosphorus Loading to Final Clarifier and Corresponding Al Dosage Pattern	65
19	Elevation View of Alum Feeding System	67
20	Total Phosphorus Removal as a Function of Flow and Final Clarifier Overflow Rate for Experimental Periods 1 Through 4, and 6 Through 12	82
21	BOD Removal as a Function of Flow and Final Clarifier Overflow Rate for Experimental Periods 1 Through 4, and 6 Through 12	83
22	Total Suspended Solids Removal as a Function of Flow and Final Clarifier Overflow Rate for Experimental Periods 1 Through 4, and 6 Through 12	84
23	Effect of Flow on Total Phosphorus Removal from Sorting Analysis	89
24	Scattergram for Alum Concentration Dosage versus Percent Total Phosphorus Removal	90
25	Scattergram for Al:Influent TP (Mole) versus Percent Total Phosphorus Removal	91
26	Scattergram for Flow versus Percent Total Phosphorus Removal	92
27	Effect of Alum Concentration Dosage on Total Phosphorus Removal from Sorting Analysis	93

TABLES

Number		Page
1	Characteristics of Plant Influent - September 1969-February 1972 (Monthly Averages)	10
2	Ratio of Total Inorganic to Total Phosphorus Concentration in Plant Influent	11
3	Phosphorus Concentration at Various Points in Plant Flow Scheme, Mason Farm Treatment Plant, April 1970-March 1971	12
4	Diurnal and Weekday Variations in Influent Orthophosphate Concentration and Loading	14
5	Analytical Procedures	15,16
6	Jar Test Results for Lime Addition to Trickling Filter Effluent	20
7	Effect of Cationic Polyelectrolyte on Phosphate Removal from Plant Effluent at Constant Lime Dose, pH 9.3	23
8	Polynomial Regression Models of Choice for Phosphorus Removal with Alum Addition	27
9	Alum Dosages Required for 97-98 Percent Removal of Total Phosphorus	27
10	Ratio of Aluminum to Total Inorganic Phosphorus Required for 97-98 Percent Removal of Total Phosphorus	32
11	Ratio of Aluminum to Total Phosphorus Required for 97-98 Percent Removal of Total Phosphorus	32
12	Effect of Cat-Floc and Magnifloc on Alum Precipitation of Phosphorus from Trickling Filter Effluent	34
13	Effect of Calgon WT-300 on Alum Precipitation of Phosphorus from Trickling Filter Effluent and Secondary Effluent	34
14	Effect of Natron Floc Aid on Alum Precipitation of Phosphorus from Secondary Effluent	35

TABLES (Continued)

Number		Page
15	Phosphorus Removal with Ferric Sulfate: Comparison of NaOH and $Ca(OH)_2$ for pH Control at pH 6 and pH 9	41
16	Phosphorus Removal with Ferric Sulfate: Comparison of NaOH and $Ca(OH)_2$ for pH Control at pH 7	42
17	Phosphorus Removal with Ferric Sulfate: Comparison of NaOH and $Ca(OH)_2$ for pH Control at pH 8	43
18	Effect of pH on Phosphorus Removal and Colloidal Iron Capture with Ferric Sulfate and Lime	45
19	Effect of Order of Addition of Iron and Lime on Phosphorus Removal and Colloidal Iron Capture	47
20	Comparison of Ferric Sulfate and Alum for Phosphorus Removal	48
21	Design Conditions for Trickling Filter Pilot Units	49
22	Comparison of Alum Addition (100 mg/l) to Primary Clarifier Influent, Trickling Filter Influent, and Secondary Clarifier Influent Ahead of Recirculation Takeoff Point	52,53
23	Comparison of Alum Addition (150 mg/l) to Primary Clarifier Influent, Trickling Filter Influent, and Secondary Clarifier Influent Ahead of Recirculation Takeoff Point	54,55
24	Comparison of Alum Addition (200 mg/l) to Primary Clarifier Influent, Trickling Filter Influent, and Secondary Clarifier Influent Ahead of Recirculation Takeoff Point	56,57
25	Comparison of Alum Addition (200 mg/l) to Primary Clarifier Influent and Secondary Clarifier Influent After Recirculation Takeoff Point	58
26	Characteristics of and Design Parameters for Units in Chapel Hill Wastewater Treatment Plant	63
27	Points of Sampling and Analyses Conducted for Main-Plant Alum Addition Studies	70
28	Experimental Periods for Full-Scale Phosphorus Removal Studies	72
29	Alum Dosage Programs	73
30	Main Plant Phosphorus Removal	74

TABLES (Continued)

Number		Page
31	Main Plant BOD_5 Removal	75
32	Main Plant Total Suspended Solids Removal	76
33	Main Plant Total Organic Carbon Removal	77
34	Quality of Primary Effluents from 1/27/72 to 8/30/72	85
35	Volumes and Characteristics of Sludges from Train No. 2 (Alum)	95
36	Volumes and Characteristics of Sludges from Train No. 1 (No Alum)	96
37	Sludge Production Summary for 1/25/72 to 8/27/72	97
38	Conditions in Primary Digester During Alum Treatment Investigation	98

ACKNOWLEDGMENTS

Numerous individuals were involved in the various phases of the project described in this report. The help and encouragement from the project officers, Dr. Robert Bunch and Mr. Richard Brenner of the U.S. Environmental Protection Agency, who suggested the full-scale alum studies, are gratefully acknowledged. Appreciation is also expressed to Dr. James C. Lamb III, who directed the project in its first year, and to Drs. A. Energin Eralp and Donald E. Francisco, who served as Research Associates during some phases of the contract.

The research work on the project was initiated in July 1969 under Contract No. 14-12-505. The contract, scheduled to terminate on June 6, 1972, was extended until October 6, 1972 to allow full-scale alum addition studies initiated in January 1972 to be completed. That portion of the research work covered in Contract No. 14-12-505 excluding the alum addition studies was reported in METHODS FOR IMPROVEMENT OF TRICKLING FILTER PLANT PERFORMANCE - PART I - MECHANICAL AND BIOLOGICAL OPTIMA, James C. Brown, Linda W. Little, Donald E. Francisco, and James C. Lamb III, August 1973. (19).

Assistance of graduate students in this research is gratefully acknowledged. Graduate assistants included George Budd, A. T. Rolan, Thomas Bates, William W. Sun, Enrique J. LaMotta, Martin Strauss, Robert Hanson, Ronald Sims, and Ronald Benton. The analytical laboratory staff, responsible for the numerous analyses conducted, included William C. Walker, UNC Wastewater Research Center Laboratory Supervisor; James E. Hayes, Cornelia Jones, William James, E. Patrick Jessup, Robert Moore, and Bruce DiCintio of the UNC Wastewater Research Center Laboratory; and Tony Owen and Susan Rappaport of the UNC Limnology Research Laboratory.

The cooperation and support of Cities Service Company in the studies on ferric chloride and ferric sulfate addition are appreciated.

The invaluable assistance of George Burns, research mechanic, and John Street, plant operator, is acknowledged, as is the help rendered by Ernest Rogers and Robert Parrish.

Special recognition is due Delores E. Plummer, who was responsible for the typing and retyping of reports and publications emanating from the project.

SECTION I

INTRODUCTION

Over 3,500 secondary municipal wastewater treatment plants in the United States use trickling filters as the biological units. Many of these are high-rate installations, characterized by relatively heavy rates of wastewater application with recirculation of treated effluent to dilute influent before application to the filter media. Removal of phosphorus is seldom greater than 10 percent, and usually little or no phosphorus removal occurs if digester supernatant is discharged back through the plant.

Contract No. 14-12-505 had as its overall research objective the development of information to help design engineers and operating personnel select among alternatives for improving performance of trickling filter plants. This report describes that portion of the contract research directed toward improvement of phosphorus removal and concommitant enhancement of general plant performance with the addition of phosphorus precipitation minerals to plant flow units.

The general approach was based on laboratory, pilot-, and full-scale experimental investigations. These investigations were conducted at the Mason Farm Sewage Treatment Plant in Chapel Hill, North Carolina, operated for the Town by personnel of the Department of Environmental Sciences and Engineering at the University of North Carolina. The most recent plant enlargement (1968) included modifications to provide unusual flexibility in full-scale operation, as well as facilities for laboratory and pilot studies. The plant is designed to permit operation as two separate parallel identical trickling filter trains between which the influent flow can be divided in any desired proportion, with capability for independent control of recirculation and other aspects of operation in each. These unusual features allowed simultaneous full-scale investigation of: (1) the effect of alum dosage on phosphorus removal, (2) the effect of alum addition on overall plant performance, including BOD and suspended solids removals, and (3) the effect of hydraulic loading on alum precipitation.

Preliminary phosphorus removal investigations were conducted prior to the full-scale studies. These investigations included a review of the literature pertinent to phosphorus removal, characterization of the quality and quantity of plant flows, jar testing with several coagulants (lime, alum, and iron salts) and coagulant aids, and pilot studies to determine the effect of the point of alum addition on phosphorus removal in a high-rate trickling filter system.

After the preliminary studies and following consultation with the Project Officer, full-scale plant studies were conducted with alum. Liquid alum was added to the effluent from the trickling filter of one train only immediately prior to its introduction into that train's final settling tank. Liquid alum was not added to the other trickling filter train which served as an ideal control system, particularly during those experimental phases when plant influent flow was equally divided between the two trains. Plant flows were measured and determinations made of the constituents in the raw wastewater, the primary and final effluents, and the various sludge and recycle streams. In addition, digester performance and sludge production were closely monitored.

SECTION II

CONCLUSIONS

Investigations at the Mason Farm Wastewater Treatment Plant, Chapel Hill, North Carolina, a typical high-rate trickling filter installation, demonstrated marked improvement of phosphorus removal and concommitant enhancement of overall plant performance with addition of phosphorus-precipitating minerals. The experimental program included laboratory, pilot-, and full-scale studies. From the results of these studies, the following conclusions were reached:

1. Characteristics of Plant Influent: The concentration of phosphorus and other constituents in the plant influent varied diurnally, daily, monthly, and seasonally. Diurnal variations were the most pronounced. For example, considering diurnal variations in flow and orthophosphate concentration, orthophosphate diurnal loading ranged from 9 to 112 kg/day (19 to 246 lb/day) as P, or from 16 to 204 percent of the daily average. The relative proportion of inorganic phosphorus to total phosphorus increased during treatment, physical removal of organic phosphorus in the primary clarifier being responsible for much of this change. Diurnal variations in influent quality were largely dampened by recirculation of trickling filter effluent through the primary clarifiers so that the quality of the filter effluent was more consistent.

2. Jar Tests: With the relatively soft water indigenous to the Chapel Hill area, removal of total inorganic phosphorus to a residual of less than 1 mg/l as P required 300-400 mg/l of lime [as $Ca(OH)_2$] with a corresponding pH of 11 or greater. At pH levels substantially less than 11, lime reacted with soluble phosphorus to form a finely divided insoluble material, much of which did not settle out during the jar test procedure, but was retained on either a 0.45 µ or a 0.22 µ membrane filter. Addition of an appropriate cationic polyelectrolyte enhanced coagulation and settling of finely divided insoluble phosphorus and permitted total inorganic phosphorus removals to residuals less than 1.0 mg/l at a pH of 9.3 to 9.5 and a lime dose of about 80 mg/l. Addition of fluoride had no effect on lime precipitation of phosphorus.

   Jar test alum dosages required for 97-98 percent removal of total phosphorus vary with the degree of prior treatment, with a dose of approximately 200 mg/l [as $Al_2(SO_4)_3 \cdot 18\ H_2O$] required for plant influent and 150 mg/l for secondary effluent. However, analysis of the results on the basis of Al:TP indicate that a ratio of 1.5-1.6 (wt/wt) is required to effect the same removal, regardless of the point in the treatment sequence. Coagulant aids enhanced phosphorus removal to varying degrees.

In jar tests with iron salts, Fe(III) requirements for removal of phosphorus, solids, and turbidity were lower with ferric chloride than with ferric sulfate, but ferric sulfate produced less sludge and a stronger floc. With iron salts alone, some iron remained in the supernatant. Experiments on trickling filter effluent with ferric sulfate and alkalis (lime and sodium hydroxide) indicated that this iron "leakage" could be eliminated by control of pH to above 7. Lime was the more effective alkali. With a trickling filter effluent total phosphorus concentration of 9 mg/l as P, approximately 50 mg/l of iron and 90 mg/l of $Ca(OH)_2$ were required to obtain iron residuals of less than 1 mg/l.

3. Pilot Plant Studies: Increased phosphorus removals were observed in trickling filter pilot plant studies with increasing alum dosages up to 200 mg/l as $Al_2(SO_4)_3 \cdot 18\ H_2O$ (the highest dose tested). Alum addition to trickling filter influent or to trickling filter effluent above the takeoff point of recirculation was less effective than addition to primary clarifier influent or to trickling filter effluent below the takeoff point of recirculation. Overall removals of BOD_5, total organic carbon, and phosphorus were essentially the same when alum was dosed to primary clarifier influent or to trickling filter effluent below the takeoff point of recirculation.

4. Full-Scale Studies: Following jar tests and pilot plant studies, full-scale were initiated with alum addition. Liquid alum was added to the influent of the final clarifier of one of two parallel trains at the Chapel Hill, North Carolina Wastewater Treatment Plant during the period from January 25 through October 5, 1972. The other train was not dosed and served as a control when influent flow was equally divided between the two trains. The Chapel Hill plant is a typical high-rate trickling filter facility. The two parallel trains consist of identical clarifier, trickling filter, and final clarifier units. Single primary and secondary anaerobic digesters treat the sludge from the two trains. The objective of the experimental program was to explore the potential for achieving efficient phosphorus removal and generally enhancing overall plant performance with alum addition to this type of municipal wastewater treatment plant.

During most of the experimental program, influent flow was divided equally between the two plant trains. Alum was applied on a three-step per day basis to approximately match the phosphorus loading entering the final clarifier of the dosed train. Alum dosage varied from 143 to 245 mg/l, and the Al:influent TP (mole) varied from 1.0 to 2.7 during the eighteen experimental periods of the investigation. During periods of equal flow division (15 of the 18 periods), influent flow to each train averaged 5,299 m^3/day (1.40 mgd), recirculation flow around the filters 7,040 m^3/day (1.86 mgd), plant influent total phosphorus 11.9 mg/l, plant influent BOD_5 170 mg/l, plant influent total suspended solids 244 mg/l, and plant influent total organic carbon 180 mg/l. Corresponding final effluent concentrations for the alum dosed train for the same 15 periods averaged 2.4 mg/l total phosphorus (79 percent removal), 16 mg/l BOD_5 (91 percent removal), 30 mg/l total suspended solids (88 percent removal), and 24 mg/l total organic carbon (87 percent removal). These values are contrasted to the average final effluent concentrations of the non-dosed control train for the 15 periods; total phosphorus 9.7 mg/l (18 percent removal), BOD_5 39 mg/l (84 percent removal), total suspended solids 54 mg/l (78 percent removal), and total organic carbon 54 mg/l (70 percent removal). During five of the 15 equal flow division periods, small amounts of different polyelectrolytes were added to the dosed train final clarifier in conjunction with alum. No improvement in performance was noted with the combination dosing over alum addition alone. The surface overflow rate of the dosed final clarifier, more than either alum concentration dosage or Al: influent TP, was the most significant operating parameter affecting solids capture and overall removal efficiencies.

Sludge production for the two plant trains during the alum treatment investigation is summarized below:

	Train No. 2 (Alum added)	Train No. 1 (Alum not added)
Volume, Pumped, gal/mil gal	6,275	4,748
Total Solids, %	3.57	3.85
Solids Pumped, lb TS/mil gal	1,894	1,483
Volatile Fraction, %	67	76
Solids Pumped, lb VS/mil gal	1,265	1,120

Conversions:

1 gal/mil gal = 0.001 ℓ/m^3
1 lb/mil gal = 0.12 g/m^3

The mixture of alum and conventional primary and secondary sludges to the primary digester resulted in a gradual decrease in the buffering capacity of the system. Primary digester alkalinity decreased from a normal level of over 2500 mg/l to about 1500 mg/l. Digester pH was less stable and tended to drift downward. It was necessary to add lime to correct this condition on one occasion. The primary digester functioned satisfactorily during the experimental program provided the pH was maintained above 6.8.

The most serious problem encountered was the failure of the secondary digester to produce a concentrated sludge for centrifugation and the inability to secure a reasonable quality supernatant for return to the plant head works. Secondary digester underflow (centrifuge feed) concentration decreased from a normal value of 6 to 7 percent solids to an average of 3.8

percent solids. The total suspended solids concentration of the supernatant increased from a normal level of less than 1000 mg/l to over 10,000 mg/l and remained high during the entire alum treatment investigation. The high solids content of the supernatant caused serious problems with the supernatant return system.

The digested sludge produced during the investigation was satisfactorily dewatered in a Bird Solid-Bowl Centrifuge and on sand drying beds. Because of reduced solids concentration of the centrifuge feed, however, it was necessary to operate the machine for longer periods of time.

On the basis of an alum [$Al_2(SO_4)_3 \cdot 18\ H_2O$] dose of 175 mg/l, the chemical cost of alum treatment was $41 per million gallons of wastewater treated at a unit price of $58 per ton of equivalent dry alum.

SECTION III

RECOMMENDATIONS

1. A flow paced alum feeding system should be used for application of alum in wastewater treatment plants.

2. The correct alum dosage must be determined for each wastewater. On the basis of full-scale Chapel Hill results, the alum dosage in mg/l is more significant than Al:TP (mole). However, the significant correlation of Al:TP noted in jar tests needs further study.

3. When alum is applied ahead of final clarifiers at trickling filter plants, the average surface overflow rate on the clarifiers should be limited to 500 gpd/ft^2.

4. In upgrading existing plants by application of alum ahead of final clarification, consideration should be given to the inclusion of fine solids removal facilities following clarification. Settling ponds or granular media filters may be appropriate. Additional research is needed to determine the most cost-effective fine solids removal system to follow final clarification.

5. Alum sludge results in decreased alkalinity and a lower than normal pH in anaerobic digesters. It is recommended that permanent equipment to facilitate the addition of lime to the digesters be included in plant upgrading programs where alum treatment is to be used.

6. Because of the problem encountered in settling digested sludge in the secondary digester at Chapel Hill during the alum addition study, it is recommended that separate facilities be considered for stabilizing and disposing of alum humus sludge withdrawn from final clarifiers. Further research designed to determine feasible and cost-effective methods for separate handling of this sludge should be conducted. If separate handling facilities are incorporated in plants utilizing alum addition, the need for permanent equipment to feed lime to digesters, as recommended in No. 5 above, becomes marginal.

7. Additional research at full-scale should be conducted to investigate the potential of ferric sulfate precipitation at slightly alkaline pH. Iron precipitation of phosphorus followed by adjustment of the pH to ~7.5 with lime appears to achieve high phosphorus removals with minimal iron leakage, while producing an effluent of near neutral pH.

8. Full-scale studies should be performed to compare the relative effectiveness of alum addition ahead of the primary clarifier, to trickling effluent ahead of the recirculation takeoff point, and to trickling filter effluent after the recirculation takeoff point.

SECTION IV

PRELIMINARY PHOSPHORUS REMOVAL INVESTIGATIONS

Preliminary phosphorus removal investigations were conducted prior to full-scale plant studies. These investigations included:

1. Review of the literature pertinent to phosphorus removal (1)
2. Determination of influent phosphorus levels and the diurnal, daily, monthly, and seasonal variations
3. Determination of average phosphorus concentrations at various points in the plant flow scheme
4. Jar tests for:
   a. Comparison of the effectiveness of lime, iron salts, and aluminum salts in removing phosphorus from wastewater
   b. Comparison of phosphorus removal efficiencies in wastewater after various degrees of treatment (influent, primary effluent, trickling filter effluent, secondary effluent)
   c. Determination of the probable levels of alum addition required in pilot- and full-scale studies
   d. Examination of the effectiveness of several coagulant aids in removing phosphorus
5. Pilot studies to determine the effect of the point of alum addition on phosphorus removal in a trickling filter system.

CHARACTERIZATION OF PLANT INFLUENT

Throughout the study period, routine analyses were made on composited samples of plant influent. Table I summarizes selected characteristics of the plant influent during the period from September 1969 to February 1972. During a portion of the study period, both total inorganic phosphorus (TIP) and total phosphorus (TP) concentrations were determined. The resulting ratios of TIP to TP are shown in Table 2.

In 1970-71, TP and TIP concentrations were determined at various points in the flow scheme on both plant trains; average monthly values are shown in Table 3. As indicated in this table, little or no phosphorus removal was achieved in either the primary or secondary treatment processes.

Diurnal and weekday variations in plant influent orthophosphate (OP) concentration and loading were evaluated in a special study conducted in July 1969 (2). In order to cover a representative week, samples of the wastewater influent were

TABLE I

CHARACTERISTICS OF PLANT INFLUENT*
September 1969 - February 1972
(Monthly Averages)

Month	Tot. BOD_5 mg/l	TSS mg/l	TOC mg/l	Kjeld. -N mg/l	NH_3 -N mg/l	NO_3 -N mg/l	TP mg/l as P	TIP mg/l as P	MBAS mg/l	pH	Alk. mg/l as $CaCO_3$
9/69	167	238	140	42.3	29.1	0.10	14.0	10.1	3.85		
10/69	176	262	125	38.1	27.0	0.08	8.8	7.4	3.57		
11/69	153	186	113	43.4	28.4	0.05	----	----	3.34		
12/69	170	159	107	43.8	27.3	0.05	----	----	3.43		
1/70	193	170	139	29.8	19.5	0.30	----	9.3	2.91		
2/70	182	185	124	36.6	20.0	0.30	----	8.3	2.39		
3/70	159	162	116	37.7	21.9	0.28	----	8.5	2.75		
4/70	165	150	109	37.2	23.7	0.30	----	8.2	2.76		
5/70	142	189	100	33.5	23.0	0.26	10.8	7.9	2.67		
6/70	117	169	117	33.6	21.7	0.19	11.5	8.8	3.04		
7/70	126	146	116	36.6	22.2	0.23	10.6	8.6	3.06		
8/70	176	187	112	32.2	22.2	0.16	10.3	7.9	2.57		
9/70	141	159	114	26.3	22.3	0.12	11.2	9.2	2.60		
10/70	136	198	110	37.1	26.3	0.14	11.1	8.5	3.10		
11/70	143	195	116	35.5	22.8	0.20	10.9	6.5			
12/70	150	175	130	35.8	23.2	0.14	11.6	7.5			
1/71	128	156	111	28.8	22.0	0.18	11.5	6.4		7.3	
2/71	134	156	120	28.2	20.6	0.10	8.8	6.0		7.4	141
3/71	134	163	111	28.8	20.2	0.10	8.6	5.8		7.0	133
4/71	136	189	123	31.2	26.5	0.10	9.0	6.8		7.1	131
5/71	159	172	148	30.0	25.5	0.20	9.7	5.8		7.2	152
6/71	156	195	132							7.2	150
7/71	136	168	121	30.2	20.5	0.17	10.8	8.1			
8/71	134	146	130	25.6	19.2	0.20	9.7	7.0			
9/71	188	136	142	28.1	24.7	0.50	9.4	6.7			
10/71	140	120	114								
11/71	170	167	154								
12/71	183	187	148								
1/72	170	186	146	30.6	20.3	0.26	10.9	7.4		7.0	
2/72	161	162	138	28.5	21.7	0.13	9.1	7.0		7.0	
Ave	154	174	124	31.2	23.1	0.19	10.4	7.7	3.00	7.2	141
Max	193	262	154	43.8	29.1	0.50	14.0	10.1	3.85	7.4	152
Min	126	120	100	25.6	19.2	0.05	8.8	5.9	2.39	7.0	131

*Based on analytical methods described in Table 5.

TABLE 2

RATIO OF TOTAL INORGANIC TO TOTAL PHOSPHORUS CONCENTRATION IN PLANT INFLUENT

Date	No. of Days Sampled	TIP:TP		
		Ave	Max	Min
5/70	11	0.75	0.82	0.65
6/70	12	0.78	0.85	0.76
7/70	6	0.81	0.92	0.62
8/70	9	0.76	0.83	0.62
9/70	5	0.83	0.89	0.74
10/70	3	0.72	0.83	0.61
11/70	2	0.60	0.60	0.59
12/70	7	0.61	0.70	0.52
1/71	11	0.58	0.73	0.48
2/71	12	0.68	0.78	0.53
3/71	5	0.68	0.85	0.45
4/71	2	0.77	0.78	0.75
7/71	3	0.75	0.78	0.71
8/71	7	0.73	0.80	0.55
9/71	6	0.72	0.76	0.68
1/72	7	0.70	0.90	0.56
2/72	16	0.77	0.88	0.57
3/72	21	0.73	1.00	0.61
4/72	14	0.72	0.86	0.62
5/72	16	0.76	0.94	0.65
6/72	16	0.79	1.19	0.61

Average of monthly averages 0.72
Range of monthly averages 0.58-0.81

NOTE: One-, two-, and three-day composites were analyzed in 1970. All analyses in 1971 and 1972 were performed on one-day composites.

collected on seven different days. However, to (1) collect samples during dry weather flow only and (2) avoid overloading the analytical laboratory, no attempt was made to sample on consecutive days.

On each of the seven days, sample collection started at 0001 hr and ended at 2400 hr. The 24-hr interval was subdivided into 12 two-hr sampling periods, which started and ended on even hours, during which separate composite samples

TABLE 3

PHOSPHORUS CONCENTRATION IN PLANT FLOWS
Mason Farm Treatment Plant, April 1970-March 1971

Month	Influent	P-1	P-2	F-1	F-2	S-1	S-2
TOTAL PHOSPHORUS							
Apr	11.48	-----	11.56	-----	11.00	-----	11.00
May	10.81	11.10	11.05	11.39	11.51	11.07	10.69
June	11.46	11.23	11.47	11.26	11.41	11.06	11.23
July	10.57	10.34	10.84	11.17	12.03	11.17	11.01
Aug	10.33	10.30	10.30	10.21	10.30	10.11	10.08
Sept	11.23	10.73	11.15	11.07	11.15	10.86	10.95
Oct	11.07	11.16	11.77	11.66	12.40	11.13	11.40
Nov	10.90	10.35	9.35	10.65	10.40	10.20	10.25
Dec	11.64	11.36	11.49	11.35	11.14	11.05	11.52
Jan	11.53	11.41	11.70	11.04	11.74	11.07	11.50
Feb	8.81	9.02	9.09	9.06	9.16	8.92	8.76
Mar	8.62	8.82	9.12	8.84	9.02	8.58	8.60
INORGANIC PHOSPHORUS							
Apr	8.18	8.98	9.02	9.62	9.14	9.32	9.08
May	7.92	9.59	8.92	9.69	9.13	9.72	8.94
June	8.85	9.55	9.79	9.89	9.82	9.71	9.82
July	8.61	9.20	9.10	9.26	9.46	8.40	9.16
Aug	7.88	8.53	8.71	8.51	8.87	8.69	9.01
Sept	9.17	9.37	9.59	10.10	9.05	9.77	9.37
Oct	8.49	9.01	8.90	9.66	9.46	9.21	8.79
Nov	6.50	7.55	6.65	8.35	6.85	7.25	6.95
Dec	7.46	8.15	8.19	8.39	7.95	8.50	8.24
Jan	6.42	7.48	7.29	7.64	7.70	7.72	7.64
Feb	5.95	6.85	6.87	7.10	7.24	7.08	7.11
Mar	5.34	6.56	6.50	6.60	6.42	6.40	6.32
$\frac{IP}{TP} \times 100$							
Apr	71.25	-----	78.03	-----	83.10	-----	82.54
May	73.26	86.39	80.72	85.07	79.32	87.84	83.63
June	77.22	85.04	85.35	87.83	86.06	87.79	87.44
July	81.46	88.97	83.95	82.90	78.64	75.20	83.20
Aug	76.33	82.82	84.56	83.35	86.17	85.95	89.38
Sept	81.70	87.32	86.01	91.24	81.16	89.96	85.57
Oct	76.69	80.73	75.62	82.85	76.29	82.75	77.10
Nov	59.63	72.95	71.12	78.40	65.86	71.08	67.80
Dec	64.09	71.74	71.28	73.92	71.36	76.92	71.53
Jan	55.68	65.60	62.31	69.20	65.59	69.74	66.46
Feb	67.53	75.94	75.58	78.37	79.04	79.37	81.16
Mar	67.75	74.37	71.27	74.66	71.18	74.59	73.49

Legend: P - Primary Clarifier Effluent; F - Trickling Filter Effluent
S - Secondary Clarifier Effluent; 1 and 2 - Systems Numbers

of influent were collected. The even hour periods were selected after preliminary study of previous influent flow records indicated relatively less change in flow during these periods as opposed to those 2-hr periods starting and ending on odd hours.

The composite sample collected during each two-hr period was composed of eight 120-ml portions collected at 15-min intervals. The first portion was collected 15 min after the start of the sampling period, the last at the end of the two-hr period. Samples were not composited according to flow since previous flow records showed relatively little change in flow magnitude during each period with the exception of the periods from 0001-0200 hr and 0800-1000 hr. The unfiltered samples were preserved with mercuric chloride and refrigerated until analyzed for OP.

Flow data were obtained from the main-plant records. Influent flow is measured in a stilling well connected to a Parshall flume, and the signal transmitted to a strip chart recorder.

Results of the above intensive seven-day study are presented in Table 4. Week-day variations in OP loading were relatively small, ranging from 42 to 54 kg/day (92 to 118 lb/day) as P. Diurnal variations in concentration in contrast were large, ranging from 36.4 percent (0600-0800 hr) to 151 percent (1200-1400 hr) of the daily average. When flow was considered and OP loading calculated, diurnal variations were even more pronounced, ranging from 9 to 112 kg/day (19 to 246 lb/day) as P, or from 16 to 204 percent of the daily average.

JAR TESTS

Materials and Methods

In a typical jar test, the sample was subjected to rapid mixing on a magnetic stirrer for 30 sec, then transferred to a gang stirrer (Eberbach or Phipps & Bird) for 30 min of flocculation mixing at 30 rpm. After completion of mixing, the sample was allowed to settle quiescently for 30 min before collection of the supernatant for analysis.

Test jars were 1.5 liter battery jars or 1 qt Kerr wide-mouth jars. Unless otherwise stated, test chemical solutions were freshly prepared from reagent or purified grade chemicals. Distilled water was employed in preparation of stock solutions.

Turbidity was measured with a Hach Laboratory Turbidimeter Model 2100 (Hach Chemical Co., Ames, Iowa). pH was measured with a Leeds & Northrup pH Meter Series 7400-A2 or a Fisher Accumet pH Meter Model 310. Sludge volumes were measured utilizing plastic or glass 1 liter Imhoff cones, allowing 30 min settling time. Other analyses were performed as indicated in Table 5.

TABLE 4

DIURNAL AND WEEKDAY VARIATIONS IN INFLUENT ORTHOPHOSPHATE CONCENTRATION AND LOADING

Time	Orthophosphate, mg/l as P									Loading	
	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Ave	% of Ave	lb/day as P	% of ave
0001-0200	8.3	6.6	8.0	6.8	6.6	8.5	8.3	7.6	94.2	94	78.4
0200-0400	6.2	5.5	5.8	4.4	4.8	6.0	6.7	5.6	69.9	44	36.3
0400-0600	4.0	4.7	4.6	3.1	3.4	4.2	4.9	4.1	51.3	24	20.0
0600-0800	2.9	3.1	3.2	2.5	2.7	3.1	3.0	2.9	36.4	19	16.0
0800-1000	2.4	4.7	4.6	4.1	9.6	4.7	4.0	4.9	60.5	81	67.2
1000-1200	7.6	11.4	11.7	8.5	4.1	10.9	10.4	9.2	114.6	198	164.5
1200-1400	11.9	12.9	12.2	10.6	11.9	12.0	13.4	12.1	150.6	246	204.4
1400-1600	10.6	10.8	12.0	9.5	10.5	11.4	13.6	11.2	139.0	225	187.2
1600-1800	10.9	10.2	10.6	9.6	9.9	11.1	11.7	10.6	131.2	190	158.4
1800-2000	9.7	11.4	9.2	7.4	9.5	10.1	10.1	9.6	119.5	166	138.2
2000-2200	8.7	9.6	9.8	8.7	9.8	9.1	9.5	9.3	115.6	155	129.2
2200-2400	8.4	9.1	10.8	8.0	10.1	10.1	9.6	9.4	117.2	152	126.4
Ave	7.6	8.3	8.5	6.9	7.7	8.4	8.8	8.0	100.0	120	100.0
% of Ave	94.2	103.4	106.0	86.1	96.1	105.0	110.0				
Loading lb/day as P	92	133	132	113	123	128	118				

Note: 1 lb/day = 0.4536 kg/day

TABLE 5

ANALYTICAL PROCEDURES

PARAMETER	METHOD	SOURCE**
Alkalinity, Total (as $CaCO_3$)	Electrometric Titration - pH 4.5	1
Biochemical Oxygen Demand (BOD, 5 day, 20 °C)	YSI DO Analyzer (probe method) (modified blank depletion)	2
Carbon - Inorganic Organic (TOC)	Dow-Beckman Carbonaceous Analyzer Model No. 915 (Dual Channel)	1
Chemical Oxygen Demand (COD)	Dichromate reflux - 0.25 N	2
Chloride (Cl^-)	Mercuric Nitrate Titration	2
Dissolved Oxygen	Winkler Azide or YSI DO Analyzer (probe method)	2
Methylene Blue Active Substances (MBAS)	Methylene Blue	2
Metals, Total	Perkin-Elmer Model 303 Atomic Absorption Unit	1
Dissolved	Filtration through 0.45 μ membrane filter	
Nitrogen, Ammonia (NH_4^+-N)	Technicon AutoAnalyzer - Sodium Phenolate	1
Nitrogen, Kjeldahl, Total (Kjeld-N)	Technicon AutoAnalyzer - Digestion + Phenolate	1
Nitrogen, Nitrate (NO_3^--N)	Technicon AutoAnalyzer - Hydrazine Reduction	1
Nitrogen, Nitrite (NO_2^--N)	Technicon AutoAnalyzer - Diazotization	1
pH	Electrometric	2
Total Phosphorus (TP)	Persulfate Digestion + Technicon AutoAnalyzer Automated Stannous Chloride	1
Total Inorganic Phosphorus (TIP)	Automated (single reagent) Hydrazine Sulfate Reduction Modification*	1
Soluble Phosphorus (SP)	Filtration through 0.45 μ membrane filter	1
Orthophosphate Phosphorus (OP)	Automated Stannous Chloride Method	1

TABLE 5 (continued)

ANALYTICAL PROCEDURES

PARAMETER	METHOD	SOURCE**
Solids, Total (TS)	Gravimetric, 103 °C (Method 224 A)	2
Solids, Total Volatile (TVS)	Gravimetric, 550 °C (Method 224 B)	2
Solids, Total Suspended (TSS)	Gooch Crucible Filtration, 103 °C (Method 224 C)	2
Solids, Volatile Suspended (VSS)	Gooch Crucible Filtration, 103 °C Gravimetric, 550 °C (Method 224 D)	2
Solids, Settleable	Volume (Method 224 F)	2
Solids, Total Suspended (after settling)	Method 224 C, on supernatant prepared by Method 224 F	2
Solids, Volatile Suspended (after settling)	Method 224 D, on supernatant prepared by Method 224 F	2
Solids, Mixed Liquor Suspended (MLSS)	Known volume of sample is centrifuged and solids removed are dried and weighed	UNC Wastewater Research Center method
Turbidity (JTU)	Hach Model 2100 Turbidimeter	Hach manual
Volatile Acids	Distillation Method (tentative)	3

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*Total Inorganic Phosphorus (Automated Method). The unfiltered sample is treated by mild acid hydrolysis (2.5 N H_2SO_4 at 90 °C), followed by orthophosphate determination. Ammonium molybdate reacts with phosphorus in an acid medium to form a phospho-molybdate complex. This complex is reduced to an intensely blue-colored complex by hydrazine sulfate. The color is proportional to the phosphorus concentration. The result includes dissolved and suspended orthophosphates and acid-hydrolyzable phosphates originally present in the sample.

**[1] FWPCA. 1969. *FWPCA Methods for Chemical Analysis of Water and Wastes.* U.S. Department of Interior, Federal Water Pollution Control Administration. Analytical Quality Control Laboratory, Cincinnati, Ohio.

[2] APHA, AWWA, WPCF. 1965. *Standard Methods for the Examination of Water and Wastewater, 12th edition.* American Public Health Association, Inc., New York, New York.

[3] *Ibid., 11th edition,* 1960.

Lime Precipitation

Investigations of lime precipitation of phosphorus were conducted to examine (1) the effects of lime dosage on pH, phosphorus residual, and turbidity and (2) the degree of incremental phosphorus removal achieved with filtration, coagulant aid addition, and fluoride addition in conjunction separately with lime addition.

Typical results of jar tests to examine the relationship of lime dosage to pH, phosphorus residual, and turbidity are shown in Figures 1 and 2 and Table 6. These results are consistent with those commonly reported (3). The lime dosage required to raise the pH from 9.5 to 11.5 was approximately three times that required to raise the pH from 7.5 to 9.5. As indicated in Figure 1, for Chapel Hill wastewater, which has an alkalinity of about 140 mg/l (as $CaCO_3$), 75-125 mg/l of lime [as $Ca(OH)_2$] increased the pH to 9.5, whereas an additional 225-375 mg/l were required to raise the pH from 9.5 to 11.5. To obtain TIP residuals $\leq$ 1 mg/l required a pH of 11 or higher as illustrated in Figure 2. Residual TIP and TP concentrations for 24 jar tests are summarized in Table 6. Table 6 also shows residual turbidity for each test, and, as indicated, initial increments of lime increased turbidity, but further lime addition produced a sharp decrease in turbidity.

Observations of turbidity in jar tests indicated the presence of large amounts of finely divided suspended solids at pH levels below 11. Filtration studies were conducted in conjunction with lime addition to determine if significant amounts of phosphorus were associated with these solids. Membrane filters (Millipore Filter Corporation) of 0.22 μ or 0.45 μ pore size were employed. The test filters were preceded by a prefilter and a 0.8 μ filter. Comparison of Figures 3 and 4 reveal that with both pore sizes, filtration drastically reduced the residual TIP concentration above a calcium hydroxide dose of about 50 mg/l and a pH level of about 9. In general, filtration through either membrane pore size was capable of reducing TIP to 1 mg/l or less at a calcium hydroxide dose of 100 mg/l and a pH level of 9.5. This lime dose is considerably less than that required to effect the same TIP removal by jar settling alone. This work indicated that at lower lime doses and pH levels, significant quantities of phosphorus are insolubilized but remain in suspension.

A variety of coagulant aids were tested to determine if they would enhance settleability of the finely divided particulate phosphate produced at low lime doses. Anionic, cationic, and nonionic polyelectrolytes were evaluated in preliminary experiments. The best results were obtained with cationic polyelectrolytes such as Cat-Floc (Calgon Corporation). Cat-Floc then was investigated more extensively. Using plant effluent and a lime dose sufficient to raise the pH to 9.3 [80 mg/l of lime as $Ca(OH)_2$], Cat-Floc was evaluated in doses up to 20 mg/l. Data from this study are summarized in Table 7 and Figure 5. With lime alone, TIP was reduced from 8.9 to 5.3 mg/l; with lime and Cat-Floc (3 mg/l), to 0.8 mg/l. Such experiments indicate that with addition of small amounts of cationic polyelectrolyte, about 90 percent removals of phosphorus can be achieved at a pH of 9.5 or less, which would require much less lime, reduce or eliminate the need for further pH adjustment, and reduce the amount of sludge formed.

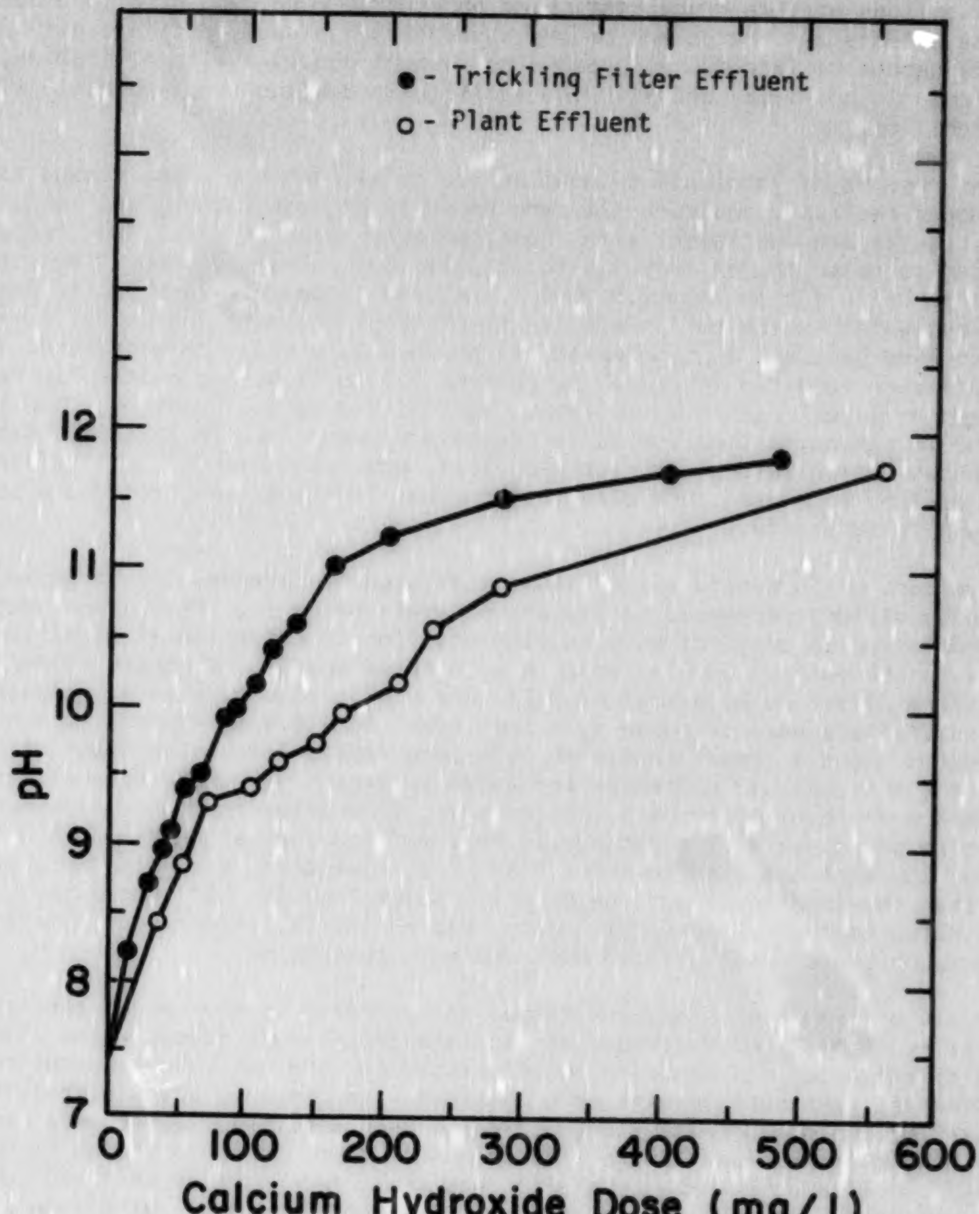


FIGURE 1. RELATIONSHIP BETWEEN pH AND CALCIUM HYDROXIDE DOSE.

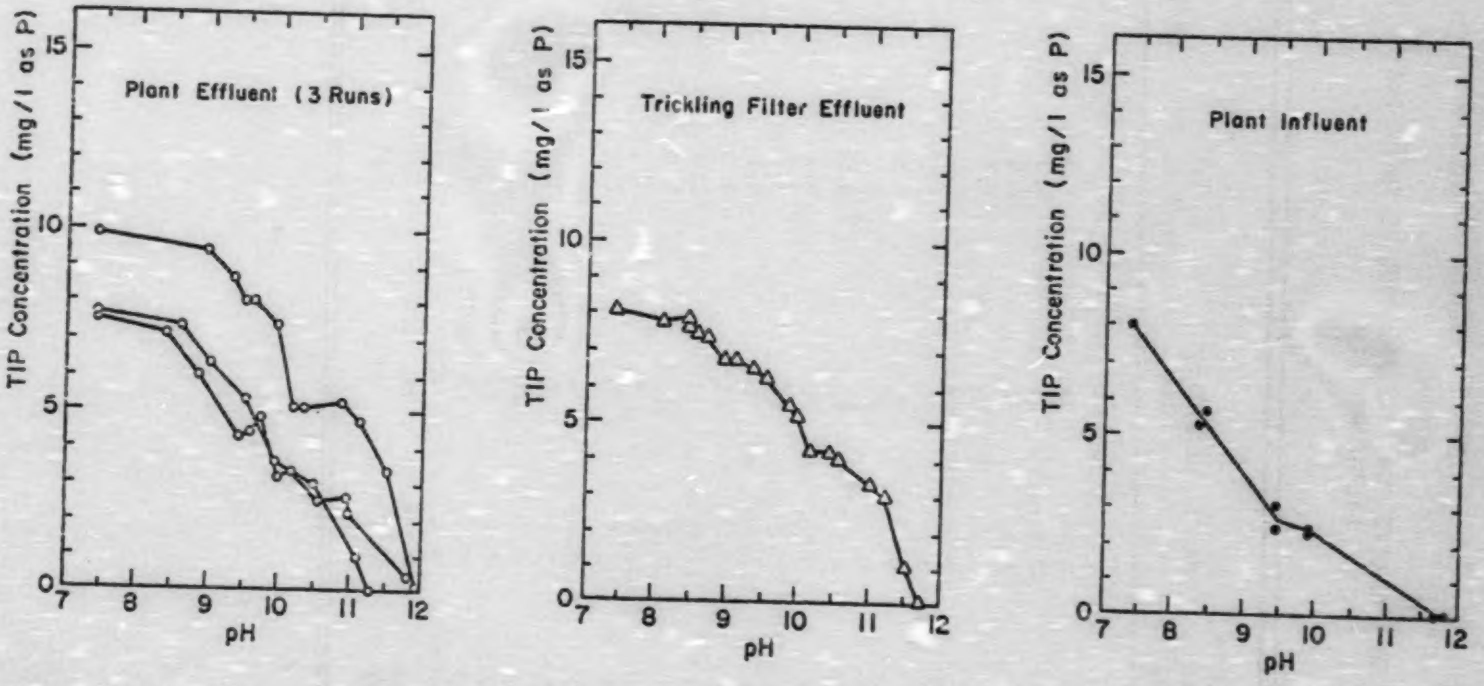


FIGURE 2. RELATIONSHIP BETWEEN pH AND RESIDUAL TOTAL INORGANIC PHOSPHATE IN VARIOUS PLANT SAMPLES.

TABLE 6

JAR TEST RESULTS FOR LIME ADDITION TO TRICKLING FILTER EFFLUENT

Jar Test Number	Lime Dose mg/l as $Ca(OH)_2$	pH	Turbidity JTU	TIP mg/l as P	TP mg/l as P
Initial Condition		7.6	30	8.0	8.7
1	0	7.3	13	8.0	8.1
2	0	7.3	14	8.0	8.3
3	25	8.7	16	7.3	7.9
4	32.5	8.9	18	6.8	7.7
5	40	9.1	20	6.8	7.4
6	52.5	9.35	22	6.5	7.5
7	65	9.5	21	6.2	7.2
8	80	9.8	20	5.5	6.0
9	90	9.95	20	5.2	5.8
10	105	10.2	15	4.2	4.9
11	120	10.4	16	4.2	4.8
12	135	10.6	15	4.0	4.4
13	160	11.0	13	3.4	3.8
14	200	11.2	15	3.0	3.6
15	280	11.5	8	1.1	2.3
16	400	11.7	0	0.1	0.3
17	480	11.8	0	<0.1	0.1
18	800	12.1	0	<0.1	<0.1
19	10	8.4	15	7.9	8.4
20	12.5	8.2	13	7.7	8.6
21	15	8.4	13	7.6	8.7
22	17.5	8.5	14	7.4	8.6
23	20	8.65	16	7.4	8.7
24	20	8.7	15	7.3	8.7

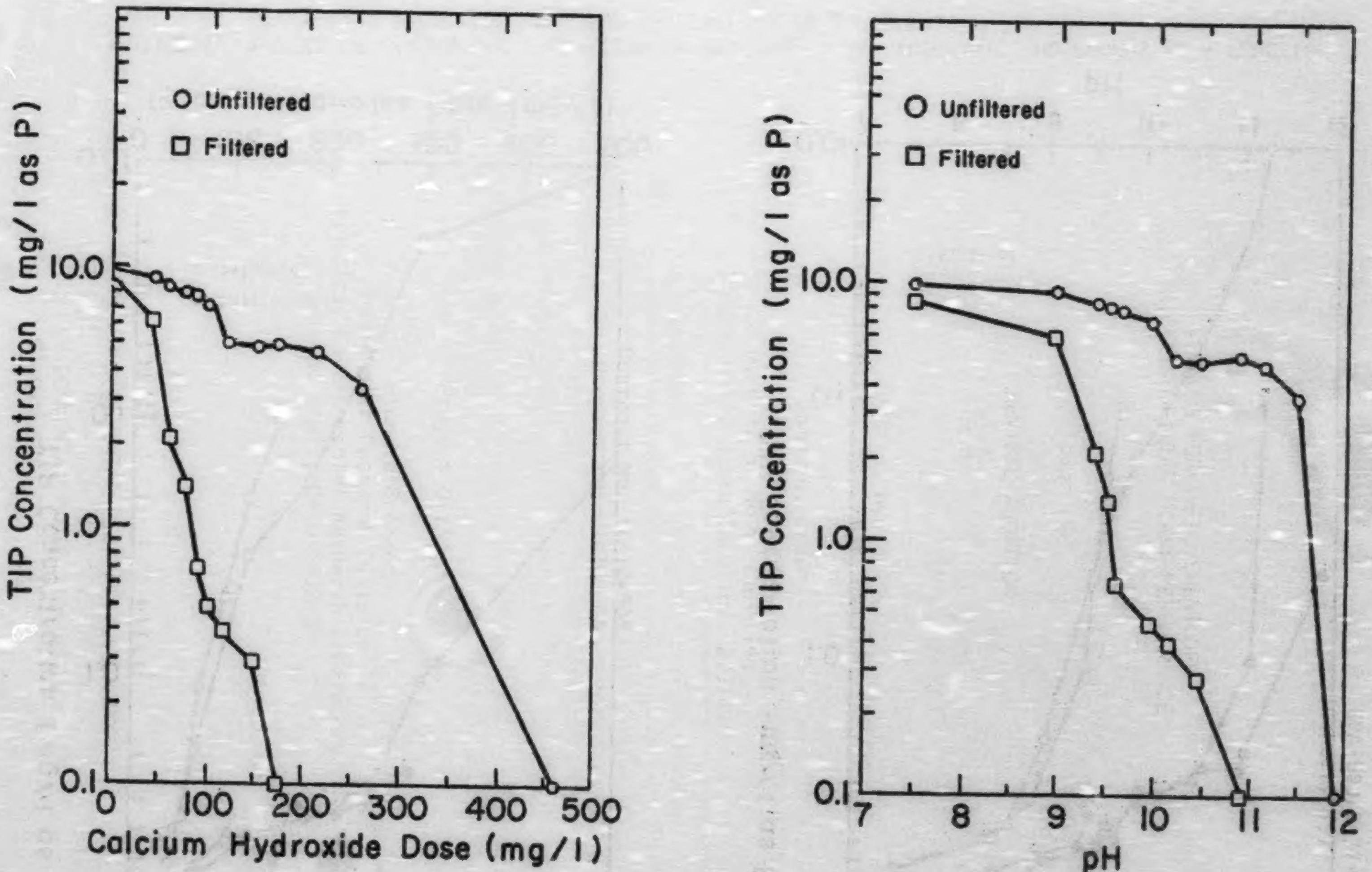


FIGURE 3. EFFECT OF LABORATORY FILTRATION ON RESIDUAL TOTAL INORGANIC PHOSPHORUS AS A FUNCTION OF CALCIUM HYDROXIDE DOSE AND pH LEVEL (0.45 μ FILTER).

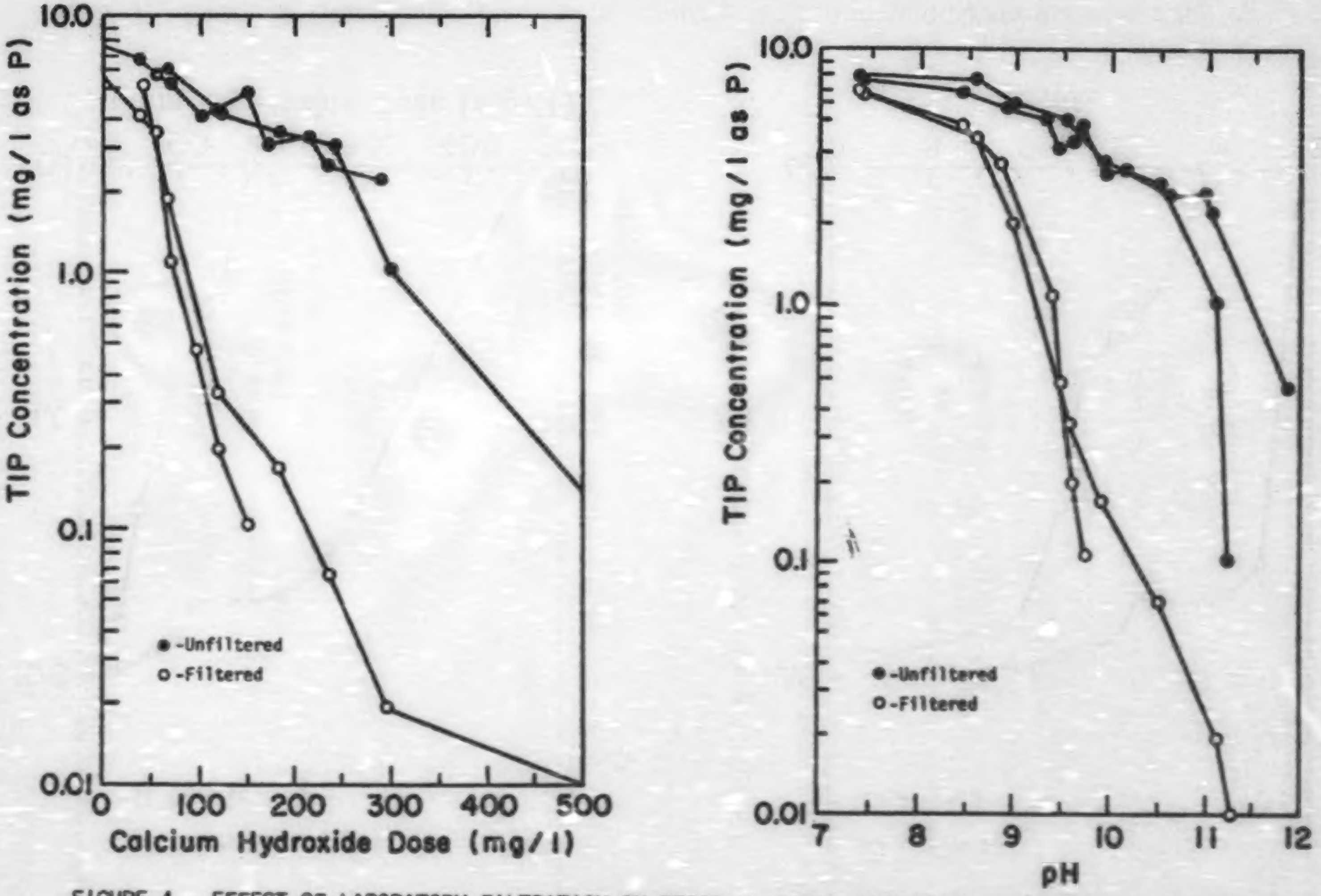


FIGURE 4. EFFECT OF LABORATORY FILTRATION ON RESIDUAL TOTAL INORGANIC PHOSPHORUS AS A FUNCTION OF CALCIUM HYDROXIDE DOSE AND pH LEVEL (0.22 µ FILTER).

TABLE 7

EFFECT OF CATIONIC POLYELECTROLYTE ON PHOSPHORUS REMOVAL FROM PLANT EFFLUENT AT CONSTANT LIME DOSE, pH 9.3

Jar Test Number	Lime Dose mg/l as $Ca(OH)_2$	pH	Polyelect. Dose mg/l	Turbidity JTU	TIP mg/l as P	TP mg/l as P
untreated		7.0	-	14	8.9	10.3
1	80	9.3	0	16	5.3	5.9
2	80	9.2	0	16	5.2	6.5
3	80	9.3	1	10	3.5	4.3
4	80	9.3	2	5	1.9	2.5
5	80	9.3	3	2	0.8	0.8
6	80	9.3	4	2	0.8	0.8
7	80	9.3	5	2	0.9	0.9
8	80	9.3	6	1	0.9	0.9
9	80	9.2	7	2	1.1	1.2
10	80	9.3	9	2	1.0	1.2
11	80	9.3	11	5	1.0	1.4
12	80	9.25	15	13	1.8	2.9
13	80	9.3	17	13	2.8	3.4
14	80	9.3	20	10	1.2	3.3

Fluorapatite [$Ca_{10}(PO_4)_6 F_2$] is a highly insoluble form of calcium phosphate (4) and conversion of soluble phosphate to this form should produce very low phosphorus residuals. Therefore, the effect of fluoride addition on lime precipitation of phosphorus using secondary effluent was evaluated. One set of samples dosed only with calcium hydroxide served as controls, while another set was dosed in addition with 10 mg/l of sodium fluoride. At the conclusion of the tests, samples were analyzed before and after filtration through a 0.22 µ filter. Results of this investigation are shown in Figure 6. Under the conditions employed, fluoride addition had little or no effect on the precipitation of phosphorus.

Alum Precipitation

When Al(III) or Fe(III) is added to a solution containing orthophoshate, the precipitation of the metal phosphate is extremely rapid, reaching completion in less than a second (5). With alum, phosphate precipitation is favored over precipitation of the hydroxide (6). Aluminum hydroxide is less efficient as a phosphate precipitant (5).

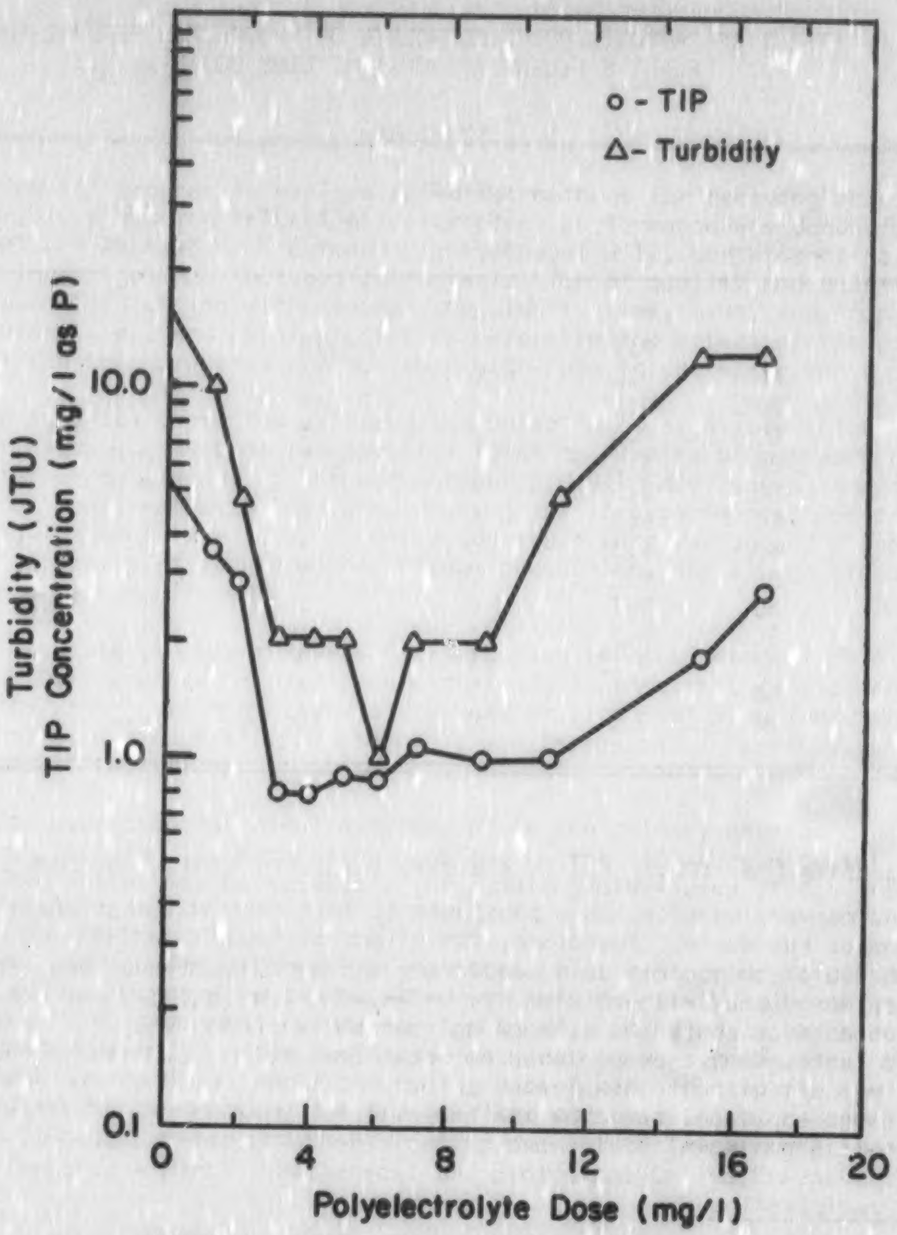


FIGURE 5. EFFECT OF CATIONIC POLYELECTROLYTE (CAT-FLOC) ADDITION ON RESIDUAL TOTAL INORGANIC PHOSPHORUS AND TURBIDITY AT A CALCIUM HYDROXIDE DOSE OF 80 MG/L AND A pH OF 9.3.

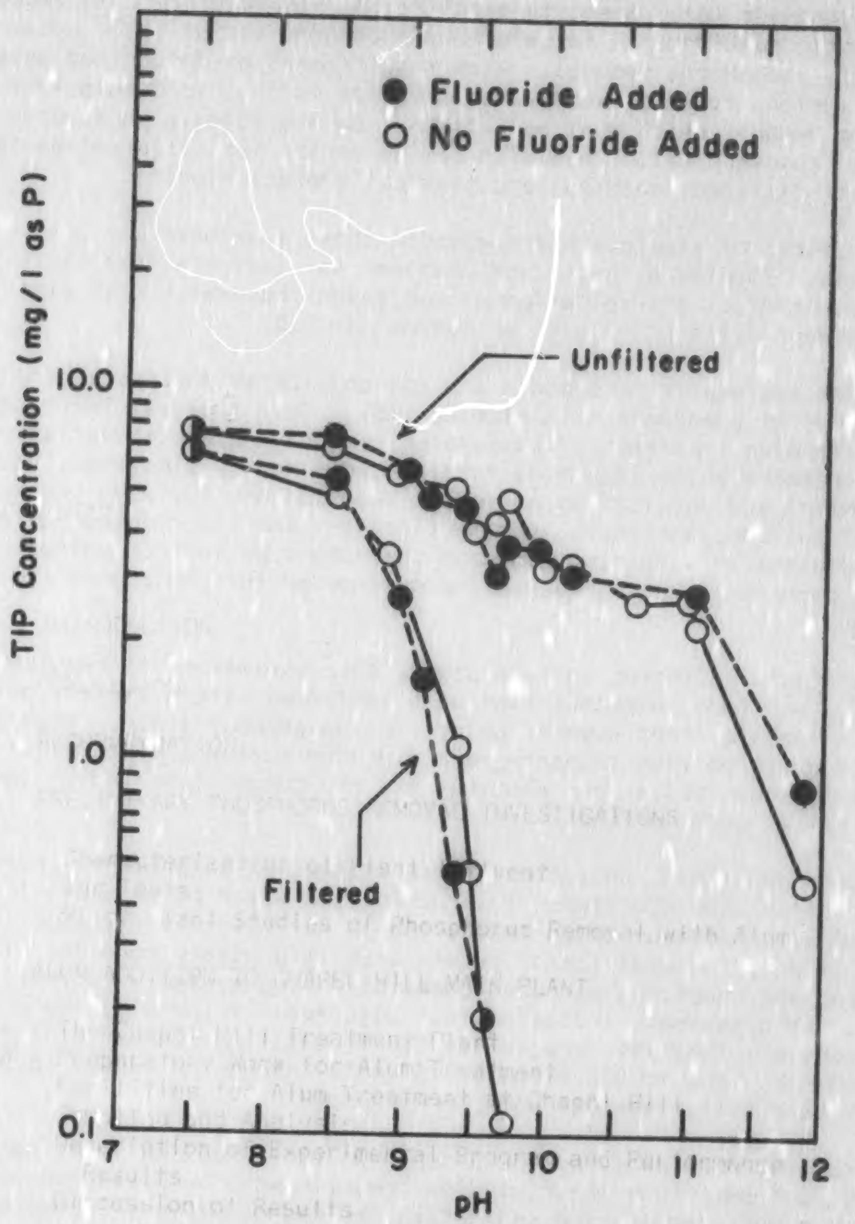


FIGURE 6. EFFECT OF SODIUM FLUORIDE ADDITION ON THE RELATIONSHIP BETWEEN pH AND RESIDUAL TOTAL INORGANIC PHOSPHORUS DURING LIME PRECIPITATION.

With wastewaters, the precipitate formed after alum addition appears to be an amorphous compound with a composition intermediate between aluminum phosphate and aluminum hydroxide (6). Also, in practice an Al:P mole ratio in excess of the stoichiometric requirements for aluminum phosphate formation is necessary for satisfactory phosphorus removal. Alum requirements as determined experimentally with various types of wastewater have led to the hypothesis that there is"an 'alum demand' which must be satisfied before soluble phosphorus can be effectively removed" (7). This alum demand varies for different wastewaters, due to their different chemical and physical characteristics.

The interactions of aluminum and condensed phosphates have not been extensively investigated. Studies by Recht and Ghassemi (5) indicate that the pH range for highly efficient precipitation of condensed phosphates with alum is very narrow, between 4.5 and 6.5 with an optimum of 5.5.

Other common wastewater components are not considered to affect directly the precipitation of phosphate with aluminum (6). Nevertheless, investigators working with alum treatment of wastewater commonly encounter variations in alum requirements which cannot be readily explained by simple analysis of the usual chemical and physical parameters. Yuan and Hsu (8) have presented evidence that sulfate, kaolinite, montmorillonite, and fluoride can affect phosphate precipitation with aluminum, and that the type and concentration of these and other components can influence the optimum pH for phosphorus removal from wastewater.

In the jar tests performed in this study, such variations in requirements were observed. Therefore, numerous runs were performed with a variety of alum dosages and samples from several points in the process train. Alum stock solutions were prepared from reagent grade aluminum sulfate [$Al_2(SO_4)_3 \cdot 18\ H_2O$]. Results from these tests were plotted, and the range of suitable alum dosages and Al:P ratios were defined.

In the tests described, unless otherwise stated, pH adjustments were not made before or after alum addition. In practice, in water of moderate to low alkalinity, addition of alum often lowers the pH sufficiently for good precipitation and if not, the addition of excess alum is probably more practical than maintaining and operating a second chemical dosing system. Further, limited tests with pH adjustment indicated that adjustment to pH 6.0, the pH of minimum orthophosphate solubility, frequently led to gasification and flotation of sludge, possibly due to CO_2 release. Slightly higher pH levels (6.5-7.0) consequently gave better overall phosphorus removal.

Treated samples were analyzed for phosphorus (total and/or total inorganic), turbidity, and pH. From these studies, results were compiled and polynomial regression models constructed indicating the degree of total phosphorus removal as a function of alum dosage, the ratio of applied Al(III) to initial total inorganic phosphorus in the respective samples, and the ratio of applied Al(III) to initial total phosphorus in the respective samples. Models were based on the following number of observations: influent, 11; primary effluent, 12; trickling filter effluent, 19; and secondary effluent, 11. In most cases, both second and third degree models were derived. The higher the degree, the more closely the function follows the observed points. The best models based on an analysis of predictability and statistical significance are given in Table 8. The models themselves are illustrated in Figures 7 to 10.

TABLE 8

POLYNOMIAL REGRESSION MODELS OF CHOICE FOR PHOSPHORUS REMOVAL WITH ALUM ADDITION

Parameter	Stream	Model Degree of Choice
Alum dosage	Influent	2
	Primary effluent	2
	Trickling filter effluent	2
	Secondary effluent	3
Al:TP	Primary effluent	2
	Trickling filter effluent	3
	Secondary effluent	3
Al:TIP	Primary effluent	2
	Trickling filter effluent	3
	Secondary effluent	3

Based on the models, alum dosages necessary for 97-98 percent removal of total phosphorus are shown in Table 9.

TABLE 9

ALUM DOSAGES REQUIRED FOR 97-98 PERCENT REMOVAL OF TOTAL PHOSPHORUS

Stream	Alum $[Al_2(SO_4)_3 \cdot 18\ H_2O]$ Required, mg/l	
	2nd Degree Model	3rd Degree Model
Influent	200*	175
Primary Effluent	180*	---
Trickling Filter Effluent	187*	170
Secondary Effluent	161	150*

*Model of Choice

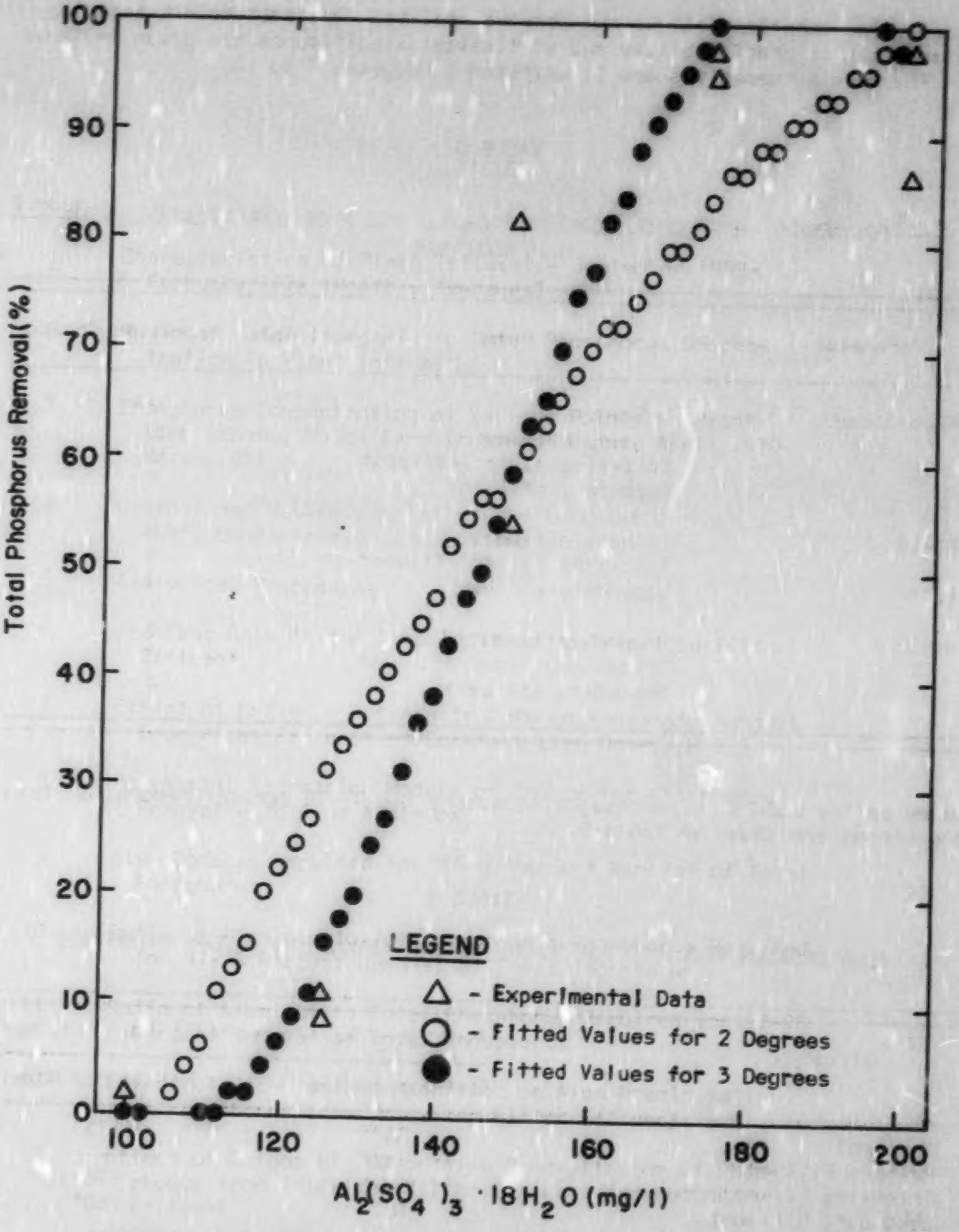
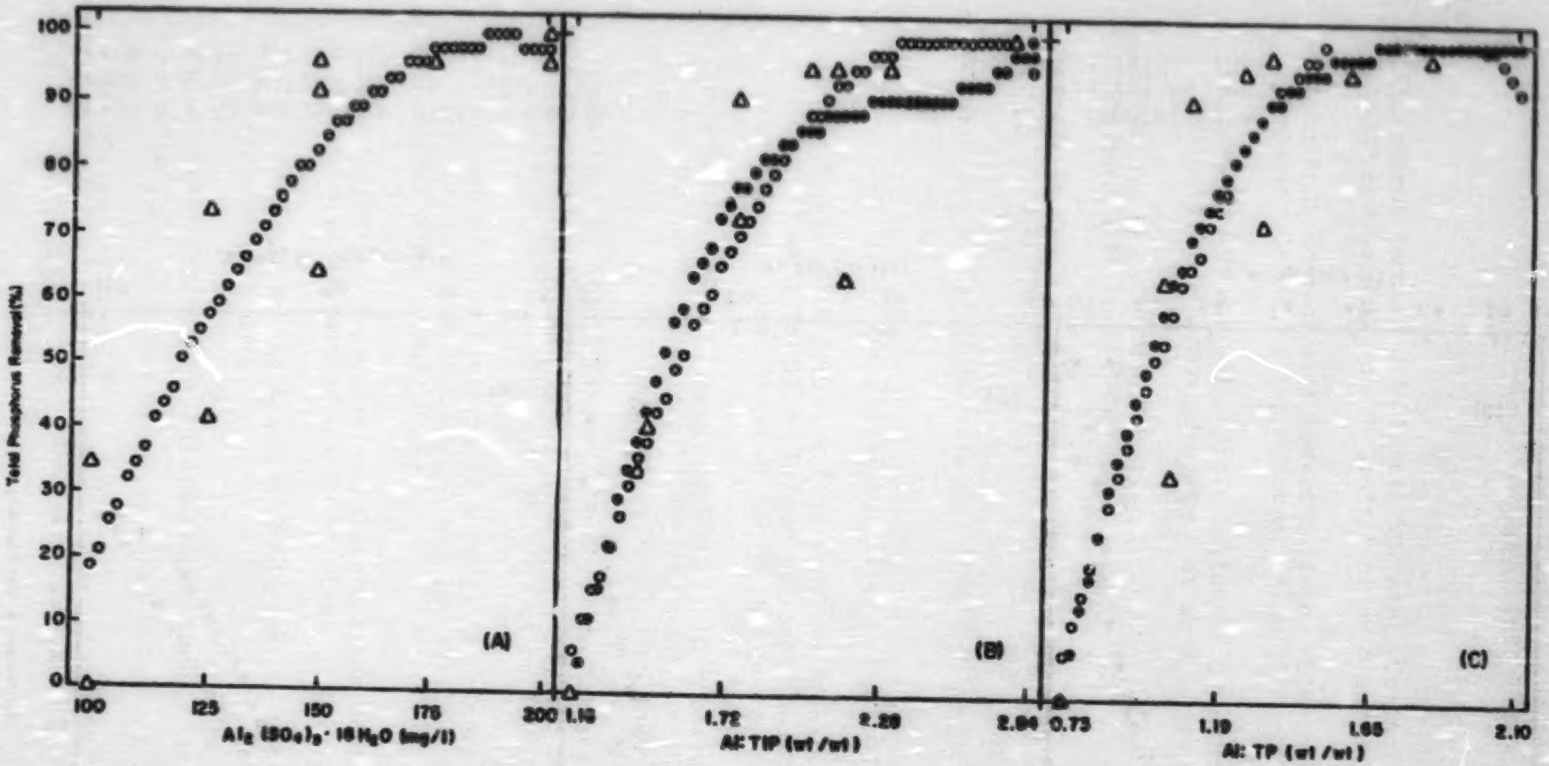


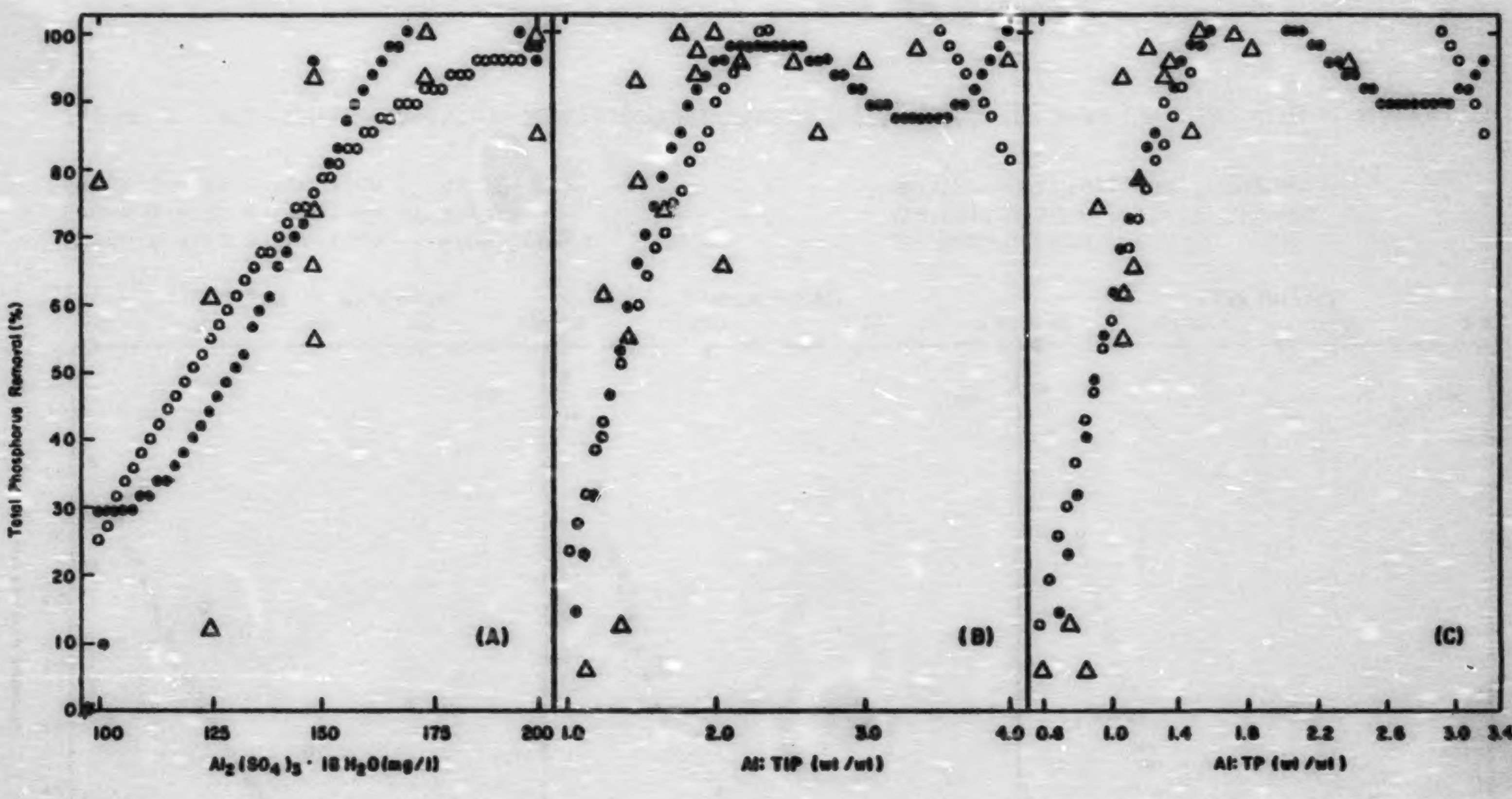
FIGURE 7. POLYNOMIAL REGRESSION MODELS FOR PHOSPHORUS REMOVAL FROM INFLUENT AS A FUNCTION OF ALUM DOSAGE.



Graph A - As a Function of Alum Dosage
Graph B - As a Function of Al:TIP
Graph C - As a Function of Al:TP

△- Experimental Data
○- Fitted Values for 2 Degrees
●- Fitted Values for 3 Degrees

FIGURE 8. POLYNOMIAL REGRESSION MODELS FOR PHOSPHORUS REMOVAL FROM PRIMARY EFFLUENT WITH ALUM ADDITION.



Graph A - As a Function of Alum Dosage
Graph B - As a Function of Al:TIP
Graph C - As a Function of Al:TP

△- Experimental Data
○- Fitted Values for 2 Degrees
●- Fitted Values for 3 Degrees

FIGURE 9. POLYNOMIAL REGRESSION MODELS FOR PHOSPHORUS REMOVAL FROM TRICKLING FILTER EFFLUENT WITH ALUM ADDITION.

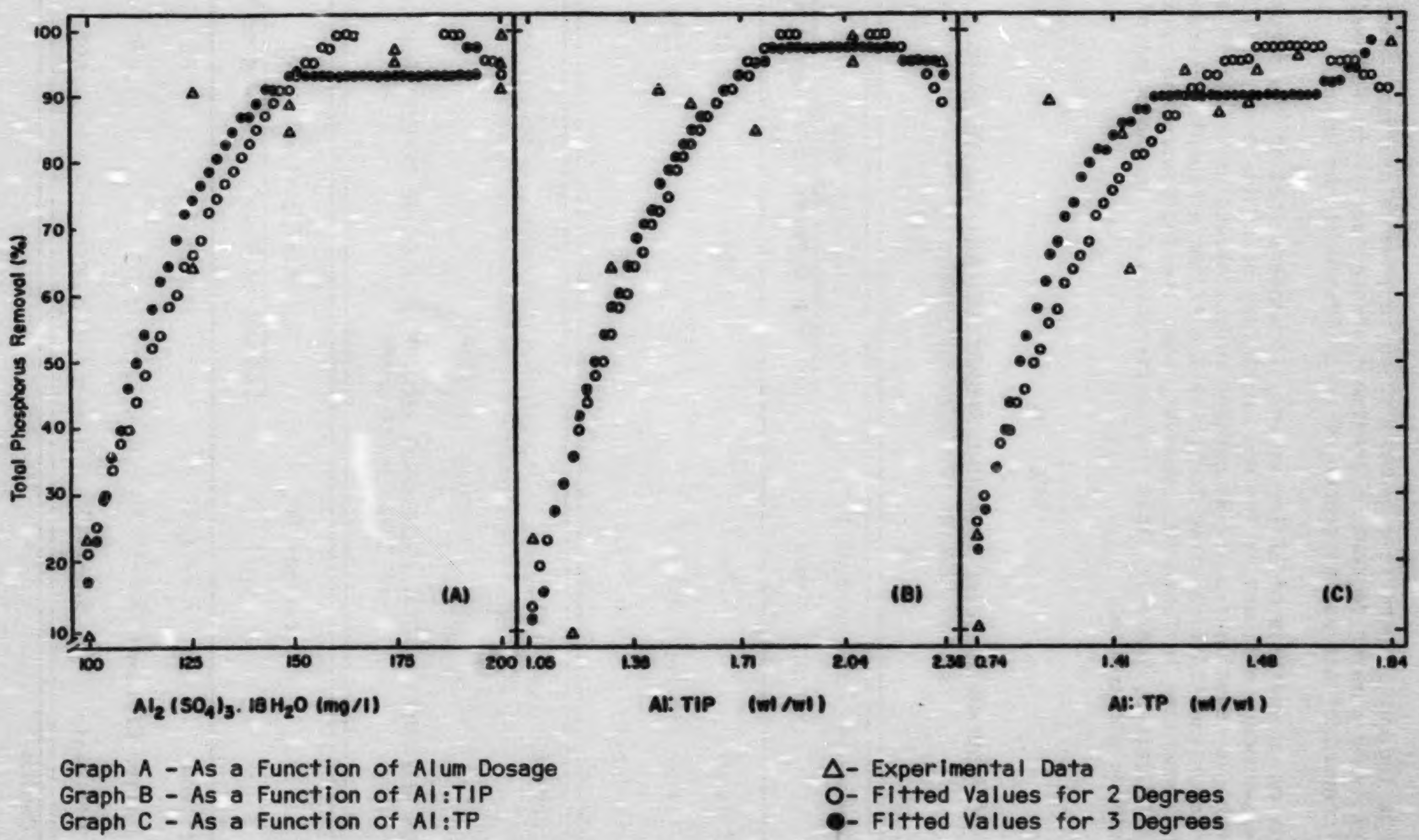


FIGURE 10. POLYNOMIAL REGRESSION MODELS FOR PHOSPHORUS REMOVAL FROM SECONDARY EFFLUENT WITH ALUM ADDITION.

These results indicate there is a general trend to lower alum requirements with progressively greater degrees of treatment, due primarily to decreasing initial TP concentrations as the degree of prior treatment increases.

Based solely on an analysis of Al:TIP values, it appears that of the streams tested, the secondary effluent is the most efficient point for alum application. Phosphorus reductions of 97-98 percent were achieved at an Al:TIP substantially lower than that required for trickling filter effluent or secondary effluent as summarized in Table 10. However, when the tests were analyzed in terms of Al:TP values, Table 11 shows that differences due to the point of alum application disappeared.

TABLE 10

RATIO OF ALUMINUM TO TOTAL INORGANIC PHOSPHORUS REQUIRED FOR 97-98 PERCENT REMOVAL OF TOTAL PHOSPHORUS

Stream	Initial TIP, mg/l	Al:TIP, wt/wt 2nd Degree Model	Al:TIP, wt/wt 3rd Degree Model
Primary Effluent	5.7-7.0	2.30*	>2.45
Trickling Filter Effluent	3.9-8.5	2.46	2.22*
Secondary Effluent	6.8-8.5	1.84	1.84*

*Model of Choice

TABLE 11

RATIO OF ALUMINUM TO TOTAL PHOSPHORUS REQUIRED FOR 97-98 PERCENT REMOVAL OF TOTAL PHOSPHORUS

Stream	Initial TP, mg/l	Al:TP, wt/wt 2nd Degree Model	Al:TP, wt/wt 3rd Degree Model
Primary Effluent	7.7-11.9	1.51*	1.65
Trickling Filter Effluent	5.0-12.9	1.60	1.63*
Secondary Effluent	8.8-11.0	1.55	1.60*

*Model of Choice

As indicated in these tables, the Al:TP values for the waste streams analyzed most uniformly predicted the amount of alum required to achieve essentially complete total phosphorus removal, irrespective of the degree of prior treatment. While this statement may seem somewhat obvious, the literature (3, 10) reveals many instances where alum dosage is chosen on the basis of the type of waste stream, Al:TIP values or Al:soluble phosphorus values. Despite the fact that the total phosphorus determination requires digestion of a sample prior to phosphorus measurement, it appears that this determination should be the parameter of choice to monitor. Although there may be some disagreement over the relative significance of organic phosphorus and inorganic phosphorus in eutrophication, the ultimate availability of most organic phosphorus compounds for algal growth would appear to dictate control measurements based on total phosphorus content (11, 12, 13, 14, 15, 16, and 17).

Alum Precipitation in Conjunction with Coagulant Aid Addition

Jar tests were conducted with alum and a variety of coagulant aids to determine if significant phosphorus removal could be achieved with lower alum doses. Tests were conducted with grab samples, in most cases on a "one-shot" basis. Coagulant aids were prepared according to manufacturers' recommendations. Phosphorus removals were calculated on the basis of the phosphorus remaining in the test jar supernatant compared to that remaining in supernatant of a control jar to which nothing was added.

As shown in Table 12, with trickling filter effluent and an alum dose of 150 mg/l, phosphorus and turbidity removals were markedly enhanced by the addition of low concentrations of Cat-Floc or Magnifloc. Calgon WT-3000 somewhat improved phosphorus removal at an alum dose of 150 mg/l, especially with secondary effluent. However, improvement was not marked and was substantially less effective than was increasing the alum dose to 200 mg/l as indicated in Table 13. To a small extent, Natron Floc Aid (0.5 mg/l) improved phosphorus removal from secondary effluent at an alum dose of 150 mg/l. Similar results were obtained by increasing the alum dose alone from 150 to 175 mg/l as summarized in Table 14.

Iron Precipitation

Iron compounds effectively precipitate phosphate from wastewater. Ferric and ferrous iron compounds are being utilized currently in several large scale installations (3). However, a number of problems remain unsolved in regard to optimum utilization of iron compounds. Recent studies recommend further research in the following areas:

(1) Evaluation of the effect of ionic constituents on the efficiency of phosphate removal (5),
(2) Characterization of the sludge produced (water content, compactability, dewaterability)(3, 5, 9), and
(3) Prevention of leakage of iron into plant effluent by use of polyelectrolytes or other means (3).

TABLE 12

EFFECT OF CAT-FLOC AND MAGNIFLOC ON ALUM PRECIPITATION OF PHOSPHORUS FROM TRICKLING FILTER EFFLUENT

Sample	TP		TIP		Turbidity
	mg/l	% Removal	mg/l	% Removal	JTU
Control	11.4	----	8.5	----	20
$Al_2(SO_4)_3 \cdot 18\ H_2O$, 150 mg/l	5.5	51.8	3.9	54.1	14
+ Cat-Floc, 3 mg/l (Run 1)	0.9	92.1	0.8	90.6	2
+ Cat-Floc, 3 mg/l (Run 2)	0.8	93.0	0.7	91.8	2
+ Magnifloc, 3 mg/l (Run 1)	1.4	87.7	1.1	87.1	4
+ Magnifloc, 3 mg/l (Run 2)	1.2	89.5	1.0	88.2	4

TABLE 13

EFFECT OF CALGON WT-3000 ON ALUM PRECIPITATION OF PHOSPHORUS FROM TRICKLING FILTER EFFLUENT AND SECONDARY EFFLUENT

Sample	TP		Turbidity
	mg/l	% Removal	JTU
Trickling Filter Effluent			
Control	10.5	----	19
+ WT-3000, 0.2 mg/l	10.3	1.9	20
Alum, 150 mg/l	3.0	71.4	10
+ WT-3000, 0.1 mg/l	2.4	77.1	7
+ WT-3000, 0.2 mg/l	2.2	79.0	7
*Alum, 200 mg/l	0.4	96.2	2
Secondary Effluent			
Control	11.0	----	29
+ WT-3000, 0.2 mg/l	11.3	----	28
Alum, 150 mg/l	9.2	16.4	24
+ WT-3000, 0.1 mg/l	6.3	42.7	18
+ WT-3000, 0.2 mg/l	4.0	63.6	11
*Alum, 200 mg/l	1.3	88.2	6

*Alum as $Al_2(SO_4)_3 \cdot 18\ H_2O$

TABLE 14

EFFECT OF NATRON FLOC AID ON ALUM PRECIPITATION OF PHOSPHORUS FROM SECONDARY EFFLUENT

Sample	TP		TIP		TOC		Kjeldahl-N		NH_4-N	Turbidity
	mg/l	% Removal	mg/l	% Removal	mg/l	% Removal	mg/l	% Removal	mg/l	JTU
Control	8.8		7.7		37		41.0		20.5	9
*Alum, 100 mg/l	6.7	23.9	5.7	26.0	27	27	39.0	4.9	20.0	13
+ Natron, 0.5 mg/l	8.7	1.1	6.6	14.3	33	11	25.0	39.0	22.0	18
*Alum, 125 mg/l	3.3	62.5	2.7	64.9	18	51	37.5	8.5	20.5	7
*Alum, 150 mg/l	1.1	87.5	0.6	92.2	14	62	34.5	15.8	20.5	4
+ Natron, 0.5 mg/l	0.5	94.3	0.3	96.1	14	62	23.5	42.7	21.5	2
*Alum, 175 mg/l	0.4	95.4	0.3	96.1	12	68	31.0	24.4	20.5	2
*Alum, 200 mg/l	0.3	96.6	0.2	97.4	10	73	25.5	37.8	20.5	2

*$Al_2(SO_4)_3 \cdot 18\ H_2O$

Jar tests were conducted with iron using iron equivalent doses of 10, 20, 30, 40, and 50 mg/l. Two series of tests were conducted, one with pH control and one without.

Iron was supplied by Cities Service Company in the form of production chemicals. Ferric sulfate was supplied in dry form as Ferri-Floc, with 21.8 percent water soluble iron. Ferric chloride was supplied in liquid form as 31 percent ferric chloride (11 percent trivalent iron). Stock solutions of each chemical were prepared immediately before testing.

In each set of tests, a control jar was included. This jar was not dosed with iron, but was in all other ways treated like the test samples. The use of controls enabled distinction of the effectiveness of iron addition from the effectiveness of simple slow mixing and settling.

Tests were conducted on plant influent (after screening and grit removal) and trickling filter effluent immediately upon collection. Analyses were performed on the samples prior to chemical application and on the supernatant in the jars following chemical addition, flocculation, and settling. The number and type of analyses varied according to the type of experiment. Parameters measured included total phosphorus, soluble phosphorus (0.45μ filter procedure), BOD_5, total organic carbon, total suspended solids, total solids, pH, turbidity, total iron, soluble iron (0.45μ filter procedure), total aluminum, and soluble aluminum (0.45μ filter procedure).

Based on results of the above tests as partially summarized in Figures 11 to 14, the following conclusions can be drawn: (1) Under the conditions tested, ferric chloride was effective at lower doses than was ferric sulfate for removal of phosphorus, total suspended solids, and turbidity; (2) Sludge volume production was less with ferric sulfate and the sludge appeared stronger than that produced with ferric chloride; and (3) Some iron remained in solution with both $FeCl_3$ and $Fe_2(SO_4)_3$, as evidenced by a faint brown color.

Four additional sets of experiments were conducted with Ferri-Floc (ferric sulfate) to determine the effectiveness of pH control in and the effect of the sequence of chemical dosage on removing phosphorus. In these tests, trickling filter effluent was utilized. Chemical solutions employed in pH control were prepared from laboratory chemicals. Lime [$Ca(OH)_2$] was prepared from purified-grade power, sodium hydroxide (NaOH) and hydrochloric acid (HCl) from reagent grade liquids. Controls were utilized as previously described in this section.

First, experiments were conducted to determine whether lime or sodium hydroxide was more effective for pH control. Tests were conducted over the nominal pH range of 6 to 9. As indicated in Tables 15 to 17, phosphorus removals and control of supernatant iron were consistently better when lime was used for pH control. This difference in performance of lime and sodium hydroxide was especially marked at the lower iron doses.

Second, experiments were performed to determine the optimum pH for removal of phosphorus and elimination of effluent iron. Table 18 shows that with an Fe (III) dose of 50 mg/l, phosphorus removal was essentially the same over the

TABLE 17

PHOSPHORUS REMOVAL WITH FERRIC SULFATE: COMPARISON OF NaOH AND $Ca(OH)_2$ FOR pH CONTROL AT pH 8

Test Sample	Fe Dose mg/l	pH		Base Req'd mg/l	Supernatant				
		Before	After		pH	Turbidity JTU	Fe(Tot) mg/l	TOC mg/l	TP mg/l
Run 1:									
Control	0	7.05	----	---	7.05	21	0.8	33	9.4
Adjustment with NaOH									
I	0	7.05	8.10	*	7.65	23	0.8	32	10.7
II	20	6.20	7.95	*	7.65	21	11.5	28	5.7
III	40	5.80	8.00	*	7.60	18	11.6	22	3.4
IV	60	5.15	8.10	*	7.45	8	3.0	20	1.0
V	80	3.50	8.20	*	7.70	6	1.0	17	0.7
VI	100	3.15	8.00	*	7.55	3	0.5	46	0.5
VII	120	3.05	8.10	*	7.60	2	0.6	13	0.6
Adjustment with $Ca(OH)_2$									
I	0	7.00	8.20	26	8.00	20	0.8	34	9.1
II	20	6.20	8.30	68	7.95	14	3.8	23	3.2
III	40	6.05	8.10	74	7.55	8	3.4	49	1.3
IV	60	5.45	8.20	120	7.60	4	0.6	15	0.6
V	80	3.60	8.10	168	7.65	1	0.4	13	0.8
VI	100	3.15	8.15	200	7.50	4	0.4	—	0.6
VII	120	3.02	8.20	262	7.70	1	0.2	—	1.1
Run 2:									
Control	0	7.3	----	----	7.0	28	1.2	37	8.6
Adjustment with NaOH									
I	0	7.3	8.2	*	7.8	28	0.8	45	9.1
II	20	6.2	8.2	*	7.8	19	6.0	24	3.7
III	40	5.6	8.0	*	7.6	17	5.0	18	1.1
IV	60	4.7	8.0	*	7.6	8	1.6	15	0.4
V	80	3.3	8.0	*	7.6	12	0.9	15	0.2
VI	100	3.2	8.1	*	7.7	5	1.0	14	0.2
VII	120	3.1	8.1	*	7.6	5	1.0	13	0.2
Adjustment with $Ca(OH)_2$									
I	0	7.3	8.3	20	8.0	26	0.7	43	8.6
II	20	6.2	8.4	50	8.2	12	3.1	24	1.5
III	40	6.0	8.2	78	7.8	8	1.2	16	0.4
IV	60	4.8	8.2	114	7.4	8	0.5	14	0.2
V	80	3.4	8.0	146	7.6	12	0.5	15	0.2
VI	100	3.2	8.6	194	8.1	8	0.6	15	0.2
VII	120	3.1	8.2	266	7.7	4	0.4	14	0.1

*Amount of NaOH not measured.

nominal pH range of interest (pH 6 to 8). However, as shown in Table 18 and Figure 15, iron capture was enhanced by increasing pH to levels greater than 7. Comparison of soluble and total iron concentrations in Figure 15 indicates that removal of the insoluble iron portion was primarily responsible for the enhanced iron capture noted at the higher pH levels. It appears probable that the so-called "iron leakage" observed in practice is due to the escape of colloidal iron particles which fail to settle under the usual operating conditions. These jar tests suggest that concomitant addition of lime will improve coagulation and settling of colloidal iron.

Third, experiments were conducted to determine if any effect could be ascribed to the order of addition of iron and lime. An Fe(III) dosage of 50 mg/l was chosen. To one jar, iron was added, followed by addition of lime to the desired pH. To a similar jar, the same amount of lime was added prior to addition of the iron. Results of these tests are summarized in Table 19. Little difference was noted in phosphorus and iron removal. However, it was observed that when iron addition preceded lime addition, the floc was more compact and settled more rapidly. Incidentally, this experiment again confirmed the effectiveness of pH control for improving iron capture. With iron alone (pH 6), total iron remaining in the supernatant was 6 mg/l, contrasted with about 2 mg/l at a pH of 8.

And finally, a fourth set of additonal jar tests compared the effectiveness of alum (production liquid, 4.4 percent Al(III), Allied Chemical Company) and ferric sulfate (Ferri-Floc) in removing phosphorus at different pH levels. Iron was dosed to provide an Fe:TP of 3:1 (molar basis); aluminum, to give ratios of 1.5:1 or 1.8:1 (molar basis). At these dosages, iron compared very favorably with aluminum for phosphorus removal as summarized in Table 20. While iron "leakage" was substantial with the use of iron alone, when pH was controlled to 7 or above with lime, iron carryover was markedly reduced. It also appeared that with the wastewater sample used in this series of tests, the Fe(III) dose for effective phosphorus removal could have been reduced to 40 mg/l or less.

From the four sets of additional jar test experiments just described, the following conclusions were reached regarding chemical treatment of trickling filter effluent with ferric sulfate: (1) Iron leakage can be minimized by control of pH to 7 or above, (2) Lime is more effective than sodium hydroxide for pH control, (3) The optimum pH for iron-lime precipitation is approximately 7.5, (4) The sequential order of addition of iron and lime has little effect on phosphorus removal efficiency, (5) Using lime for pH control, ferric sulfate is superior to alum for phosphorus removal, and (6) With trickling filter effluent from the Town of Chapel Hill Treatment Plant, approximately 90 mg/l of $Ca(OH)_2$ are required to raise pH to above 7 after dosage with 50 mg/l of Fe(III) (229 mg/l of Ferri-Floc).

PILOT PLANT STUDIES OF PHOSPHORUS REMOVAL WITH ALUM

Two trickling filter pilot plants were constructed during 1966 prior to the initiation of the work reported here. Two additional trickling filter pilot plants were constructed during the course of this study. The pilot plants

TABLE 15

PHOSPHORUS REMOVAL WITH FERRIC SULFATE: COMPARISON OF NaOH AND $Ca(OH)_2$ FOR pH CONTROL AT pH 6 AND pH 9

Test Sample	Fe Dose mg/l	pH		Base Req'd mg/l	Supernatant				
		Before	After		pH	Turbidity JTU	Fe (tot) mg/l	TOC mg/l	TP mg/l
Control	0	7.00	----	----	6.85	17	0.5	48	10.6
Control + acid	0	7.00	6.05	----	6.45	18	0.6	48	10.3
Adjustment with NaOH									
I	0	6.95	9.35	*	9.00	27	0.8	56	11.1
II	40	5.72	6.00	*	6.20	8	4.4	21	1.6
III	40	5.80	8.92	*	8.70	15	6.5	28	2.3
IV	60	4.70	5.92	*	6.20	7	3.2	20	0.6
V	60	4.70	9.12	*	8.85	8	3.3	26	1.1
VI	80	3.25	6.81	*	6.60	2	0.7	14	0.3
VII	80	3.20	9.20	*	9.00	3	1.1	21	0.9
Adjustment with $Ca(OH)_2$									
I	0	6.95	9.18	100	8.95	28	0.4	38	5.6
II	40	5.85	6.35	30	6.60	7	3.0	21	0.9
III	40	5.80	9.50	170	9.15	10	0.5	20	0.5
IV	60	4.60	6.00	52	6.55	2	1.0	18	0.3
V	60	4.56	9.05	156	8.80	4	0.9	20	0.5
VI	80	3.25	6.20	120	6.65	1	0.4	16	0.3
VII	80	3.15	8.90	200	8.45	3	0.4	19	0.4

*Amount of NaOH not measured

TABLE 16

PHOSPHORUS REMOVAL WITH FERRIC SULFATE: COMPARISON OF NaOH AND $Ca(OH)_2$ FOR pH CONTROL AT pH 7

Test Sample	Fe Dose mg/l	pH		Base Req'd mg/l	Supernatant					
		Before	After		pH	Turbidity JTU	Fe(tot) mg/!	TSS mg/l	TOC mg/l	TP mg/l
Control	0	6.95	----	----	7.95	15	0.58	17	37	8.0
Iron + NaOH	40	5.90	6.95	*	6.70	6	3.07	7	19	1.3
Iron + $Ca(OH)_2$	40	5.90	7.00	58	6.90	3	1.11	10	15	0.4
Iron + NaOH	60	4.80	7.00	*	6.85	2	0.88	10	16	0.5
Iron + $Ca(OH)_2$	60	4.55	7.05	96	6.95	2	0.56	3	14	0.1
Iron + NaOH	80	3.40	6.90	*	6.80	1	0.34	8	16	0.1
Iron + $Ca(OH)_2$	80	3.40	6.92	128	6.90	<1	0.20	4	16	0.2

*Amount of NaOH not measured.

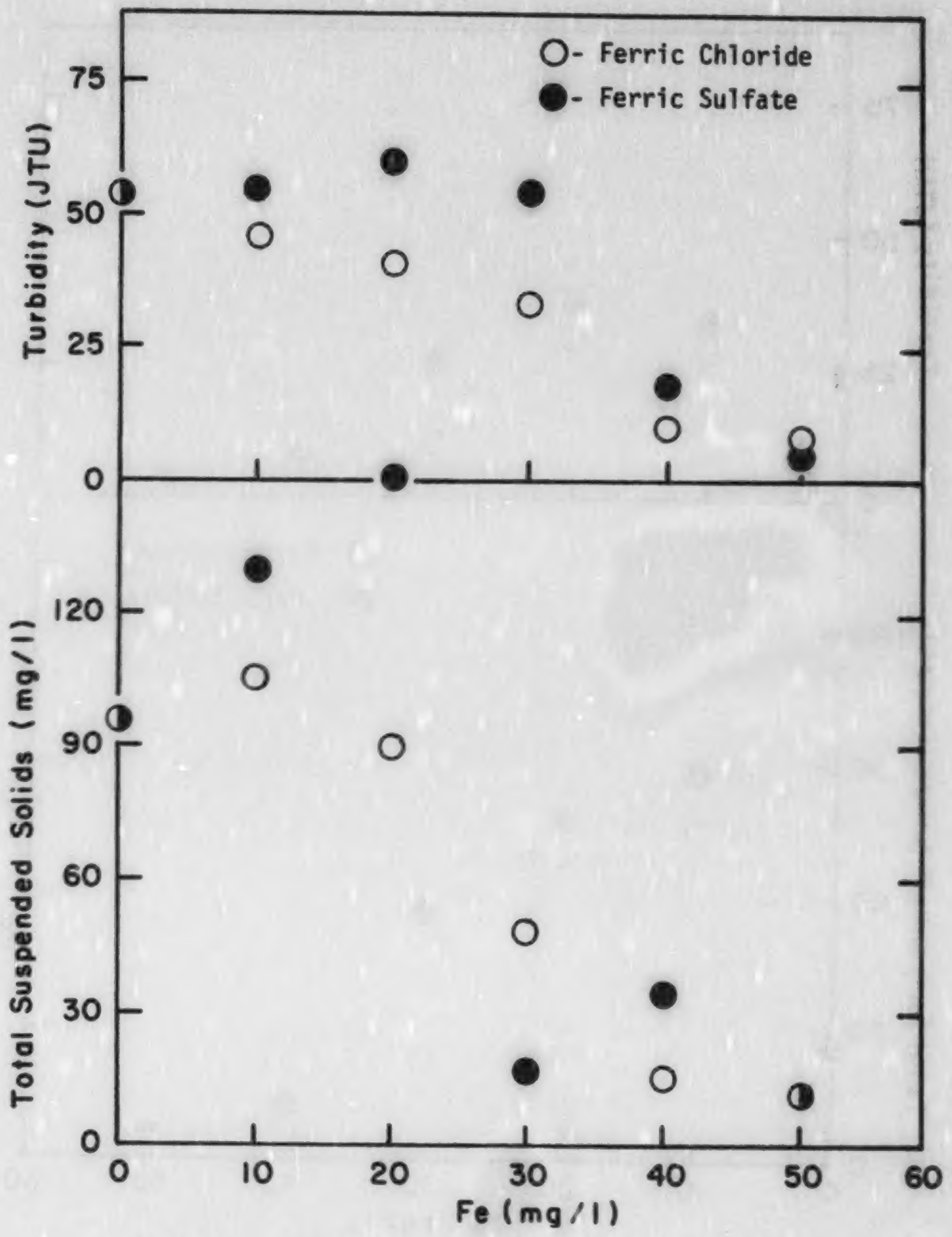


FIGURE 13. REMOVAL OF TOTAL SUSPENDED SOLIDS AND TURBIDITY FROM PLANT INFLUENT WITH FERRIC CHLORIDE AND FERRIC SULFATE ADDITION.

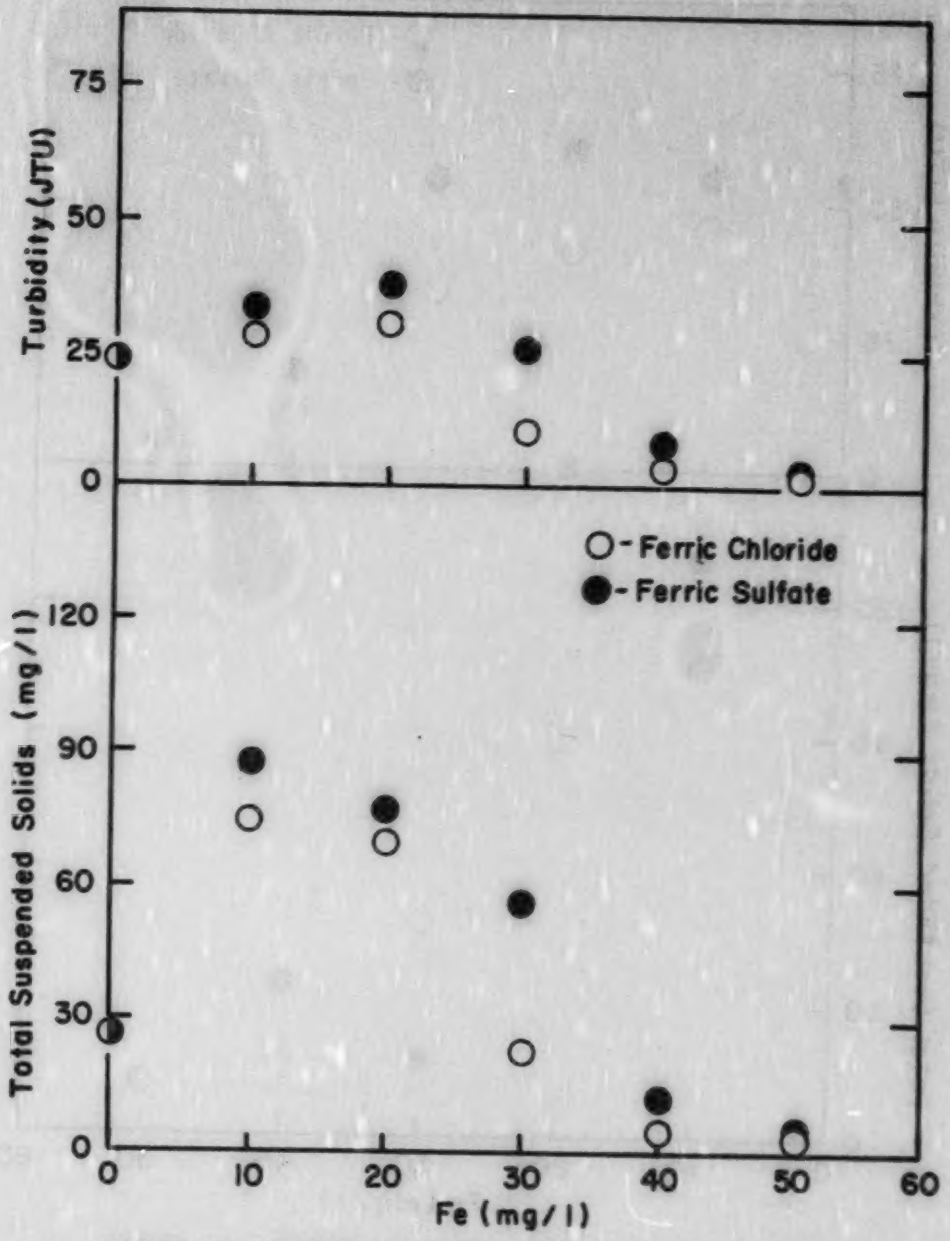


FIGURE 14. REMOVAL OF TOTAL SUSPENDED SOLIDS AND TURBIDITY FROM TRICKLING FILTER EFFLUENT WITH FERRIC CHLORIDE AND FERRIC SULFATE ADDITION.

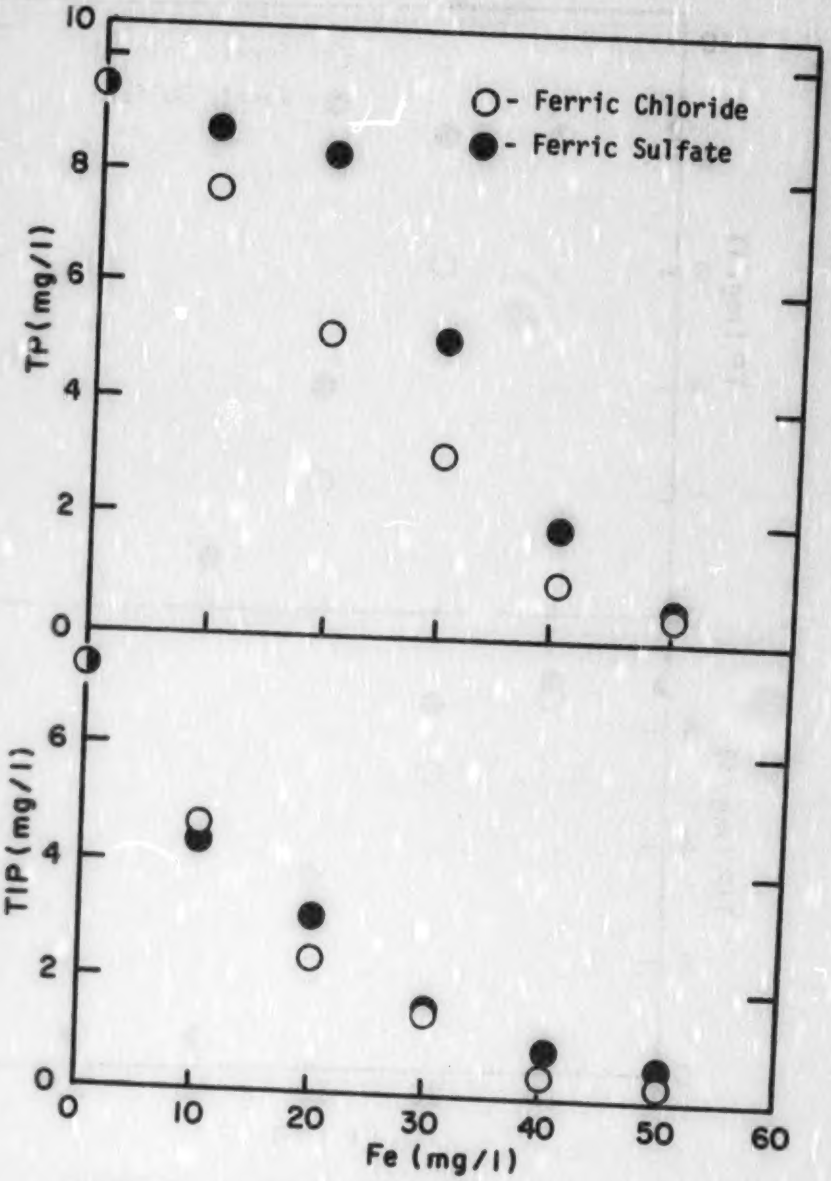


FIGURE 11. PHOSPHORUS REMOVAL FROM PLANT INFLUENT WITH FERRIC CHLORIDE AND FERRIC SULFATE ADDITION.

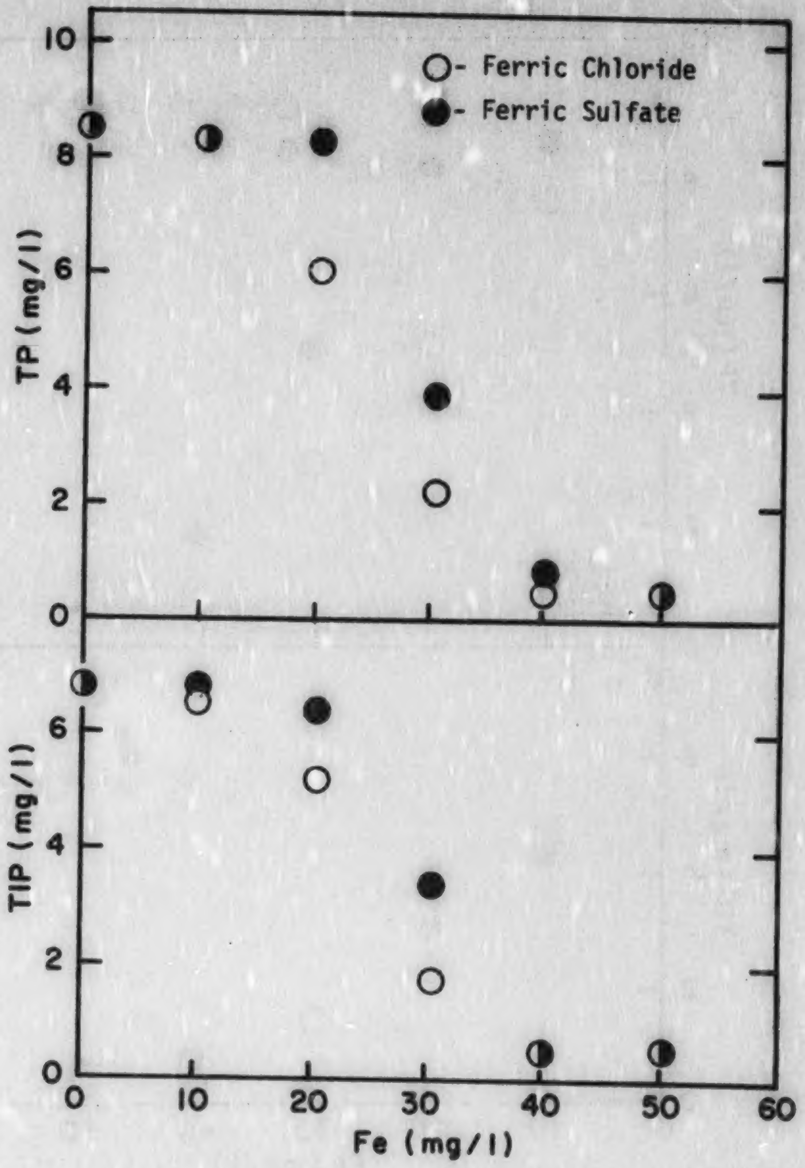


FIGURE 12. PHOSPHORUS REMOVAL FROM TRICKLING FILTER EFFLUENT WITH FERRIC CHLORIDE AND FERRIC SULFATE ADDITION.

TABLE 18

EFFECT OF pH ON PHOSPHORUS AND COLLOIDAL IRON CAPTURE WITH FERRIC SULFATE AND LIME

Test Sample	Fe Dose mg/l	pH		$Ca(OH)_2$ Req'd mg/l	Supernatant							
		Before	After		pH	Turbidity JTU	Fe(Tot) mg/l	Fe(Sol) (mg/l)	TOC mg/l	TSS mg/l	TP mg/l	P(Sol) mg/l
Sample as Collected	0				7.2	50	1.4	0.3	107	100	13.9	6.1
Control	0	7.00	6.52	---	6.6	32	0.7	0.3	78	37	11.4	8.4
Control	0	7.00	6.70	---	6.6	31	0.7	0.6	77	27	10.7	7.6
Control	0	7.00	7.00	---	6.9	32	0.6	<0.1	79	30	10.7	8.8
$Ca(OH)_2$ only	0	7.05	7.25	5	7.2	32	0.7	0.3	78	53	10.5	6.6
$Ca(OH)_2$ only	0	7.10	7.60	11	7.4	32	0.7	0.3	77	53	10.3	6.7
$Ca(OH)_2$ only	0	7.20	7.75	14	7.6	32	0.7	0.3	80	53	10.5	6.2
$Ca(OH)_2$ only	0	7.05	8.10	29	8.1	32	0.7	0.3	79	86	9.9	6.9
Iron only	50	7.00	5.80	---	5.9	6	6.0	2.7	27	10	0.6	0.2
Iron + $Ca(OH)_2$	50	5.70	6.50	47	6.5	7	3.0	0.4	28	12	1.1	0.2
Iron + $Ca(OH)_2$	50	5.78	6.72	51	6.7	6	1.6	<0.1	29	7	1.0	0.2
Iron + $Ca(OH)_2$	50	5.86	7.00	78	7.0	6	2.0	0.3	29	6	0.6	0.1
Iron + $Ca(OH)_2$	50	5.86	7.28	81	7.2	6	1.2	0.4	28	5	0.9	0.6
Iron + $Ca(OH)_2$	50	5.86	7.52	90	7.4	5	1.0	0.3	27	5	1.3	0.2
Iron + $Ca(OH)_2$	50	5.86	7.78	102	7.5	6	1.1	0.3	28	7	1.1	0.9
Iron + $Ca(OH)_2$	50	5.70	8.02	119	7.8	5	1.1	0.3	29	7	0.9	0.5

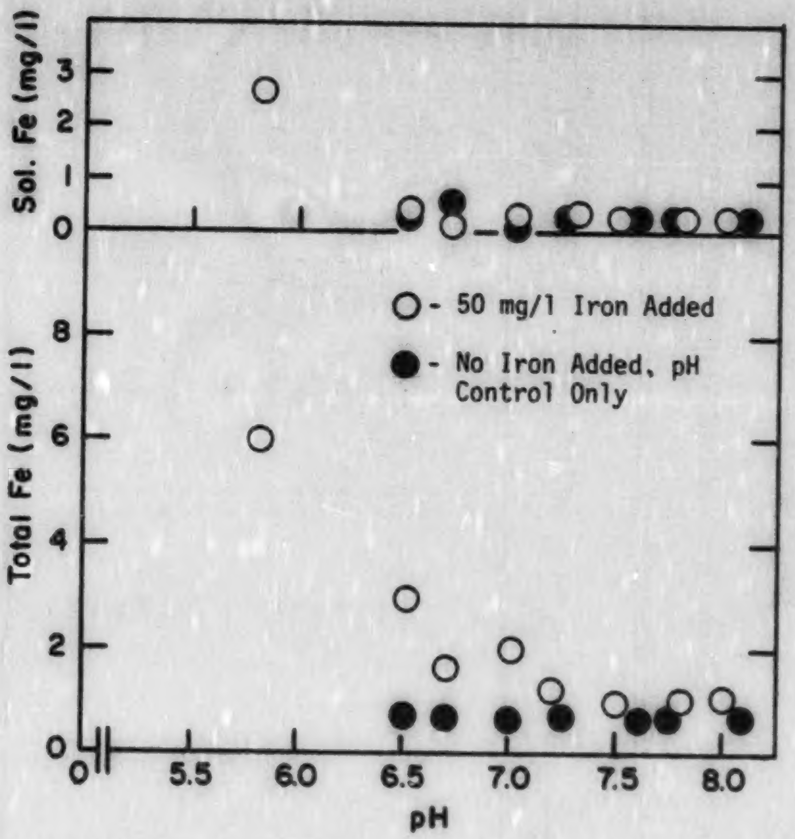


FIGURE 15. EFFECT OF pH ON Fe CAPTURE DURING IRON ADDITION FOR PHOSPHORUS REMOVAL.

TABLE 19

EFFECT OF ORDER OF ADDITION OF IRON AND LIME ON PHOSPHORUS REMOVAL AND COLLOIDAL IRON CAPTURE

Test Sample	Fe Dose mg/l	Supernatant							
		pH	Turbidity JTU	Fe(Tot) mg/l	Fe(Sol) mg/l	TOC mg/l	TSS mg/l	TP mg/l	P(Sol) mg/l
Sample as Collected	0	7.4	67	2.5	0.1	130	246	16.6	6.6
pH 7 Control	0	7.2	56	1.4	0.2	96	59	12.8	7.4
Fe, Lime	50	7.2	10	3.0	0.1	25	15	1.3	0.6
Lime, Fe	50	6.9	14	4.0	0.1	32	36	1.5	0.2
pH 8 Control	0	8.2	56	1.0	<0.1	96	117	12.4	5.9
Fe, Lime	50	7.7	9	2.1	0.1	26	14	1.0	0.2
Lime, Fe	50	7.2	10	2.0	0.1	32	21	1.0	0.4
Iron only	50	6.0	8	6.0	0.5	28	27	1.3	0.1

TABLE 20

COMPARISON OF FERRIC SULFATE AND ALUM FOR PHOSPHORUS REMOVAL

Test Sample	Metal Dose mg/l	Molar Ratio Met: TP	pH		Supernatant											
			Before	After	pH	Turbidity JTU	Metal (Tot) mg/l		Metal(Sol) mg/l		TOC mg/l	TSS mg/l	TS mg/l	TP mg/l	P(Sol) mg/l	BOD_5 mg/l
							Fe	Al	Fe	Al						
Control			6.9	---	7.2	32	1.0	2.0	0.6	0.3	79	58	313	9.0	6.1	53
Iron only	50	3:1	5.6	---	6.2	6	4.5		2.9		15	13	321	0.3	0.4	12
Iron + $Ca(OH)_2$	50	3:1	5.6	7.0	7.0	5	0.7		0.1		26	10	385	0.2	0.2	13
Iron + $Ca(OH)_2$	50	3:1	5.6	7.6	7.5	3	0.4		0.1		27	7	392	0.2	0.1	10
Iron + $Ca(OH)_2$	50	3:1	5.6	8.4	8.4	4	0.6		<0.1		28	9	363	0.2	0.1	28
Alum only	12	1.5:1	6.4	---	6.8	11		3.0		0.3	33	30	286	2.6	0.3	23
Alum, +$Ca(OH)_2$	12	1.5:1	6.4	7.0	7.2	13		3.4		0.3	30	28	333	2.4	0.3	19
Alum, +$Ca(OH)_2$	12	1.5:1	6.5	7.5	7.4	17		4.8		0.3	34	44	340	3.5	0.6	22
Alum, +$Ca(OH)_2$	12	1.5:1	6.5	8.1	7.9	12		3.2		0.4	37	25	352	2.3	0.7	20
Alum only	14	1.8:1	6.5	---	6.6	7		1.3		0.9	24	17	248	1.1	0.3	17
Alum, +$Ca(OH)_2$	14	1.8:1	6.5	7.6	7.5	5		1.4		0.2	29	15	303	0.9	0.4	17

were designed to treat raw Chapel Hill wastewater which had passed through the main plant bar rack, a degritting chamber, and a fine bar rack to remove stringy solids which would tend to clog the small pumps and pipes in the pilot plants. Influent to the pilot plants was delivered through a 2-in (5-cm) plastic pipe at a flow rate substantially in excess of pilot plant requirements. Excess flow was wasted and the desired amount of influent delivered to the operating pilot units by means of a variable speed pump with DC motors regulated by silicon controlled rectifiers. Flow to each of the pilot units was proportioned with the use of an overhead rotating distributor discharging into a circular distribution box with four equal radial sectors. Flow was by gravity from the distribution box to the primary settling tank of each pilot plant.

Each pilot plant unit consisted of a primary settling tank, a trickling filter, and a final settling tank. Recirculation was provided around the filters through the primary settling tanks, using a 2:1 recirculation ratio. A general flow diagram of a single pilot plant unit for single-stage filtration operation is shown in Figure 16.

The sizes of the settling tanks and filters were selected to provide detention times and, in the case of the filters, a hydraulic loading about the same as experienced in the main plant at a flow rate of 11,355 m^3/day (3 mgd). As the pilot settling tanks were not as deep as the main plant units, the surface overflow rates for the pilot units were substantially less than those in the main plant. All settling tanks were equipped for hydrostatic sludge removal.

The pilot trickling filters were designed to operate under conditions similar to those of the main plant filters. A filter diameter of 1.2 m (4 ft) was selected, this being considered reasonably safe for minimizing wall effects. Conventional clay tile filter underdrains were used. Filter media depth was also fixed at 1.2 m (4 ft). Inner and outer walls of the filters consisted of two vertical concentric sections of Armco steel pipe, 1.8 m (6 ft) long and 122 cm (48 in) and 137 cm (54 in) in diameter respectively. The annular space between the inner and outer pipes provided insulation to reduce heat loss during cold weather operation. Filter media was granite stone selected to pass a 9 cm (3.5 in) screen with less than 75 percent passing a 6.4 cm (2.5 in) screen.

Design conditions for the various plant units are given in Table 21 below. On the basis of an influent BOD_5 of 180 mg/l and 35 percent removal in the primary settling tanks, the organic loading on the filters approximated 1500 lb BOD_5/acre-ft/day.

TABLE 21

DESIGN CONDITIONS FOR TRICKLING FILTER PILOT UNITS

	Flow gpm	Detention Time, hrs	Overflow Rate gpd/ft^2	Hydraulic Loading mgad
Primary Settling Tank	3.6*	1.8	470	----
Trickling Filter	3.6*	---	---	18.0
Final Settling Tank	1.2	2.0	436	----

*Includes 2.4 gpm of recirculation flow

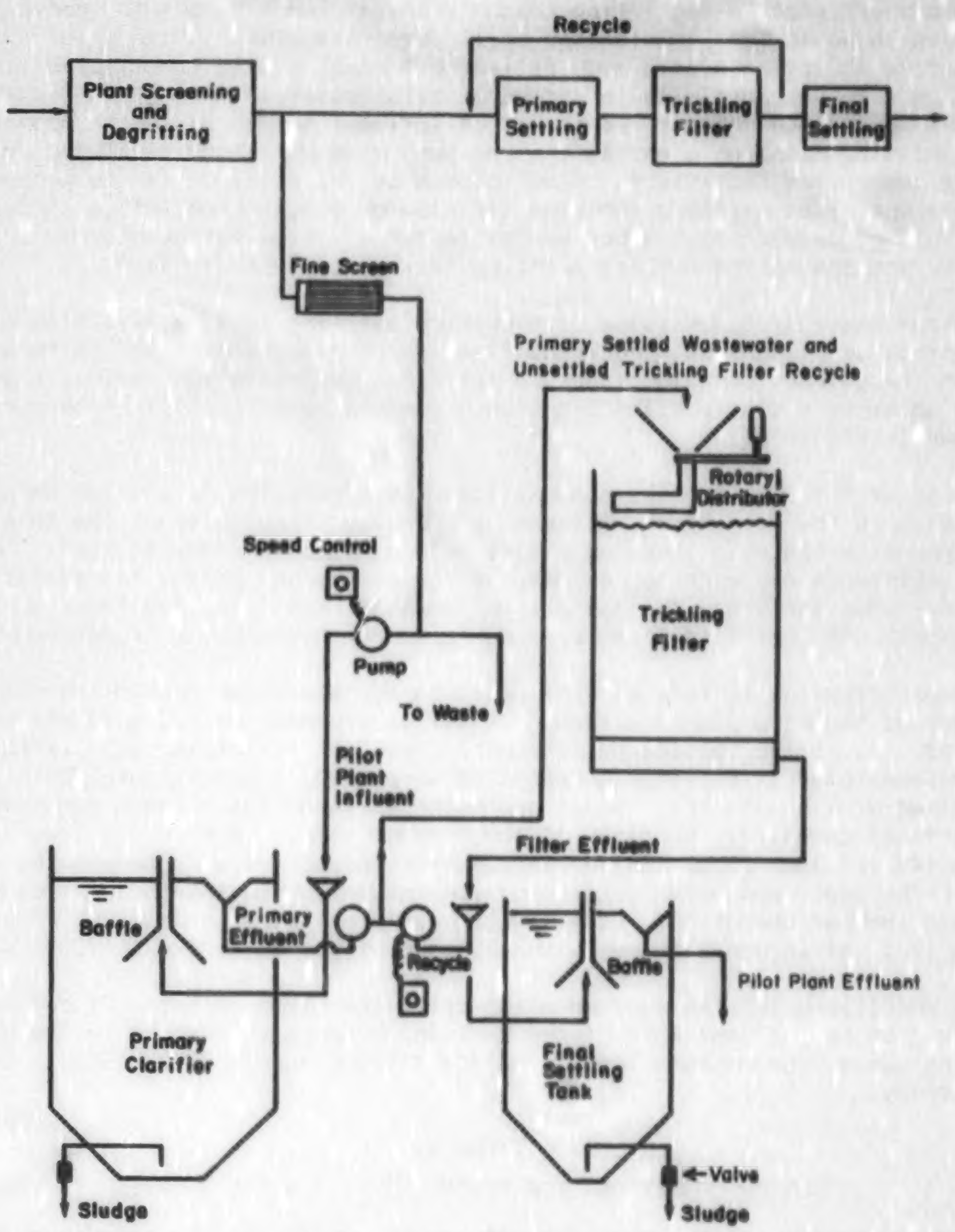

Recycle
Plant Screening and Degritting
Primary Settling
Trickling Filter
Final Settling
Fine Screen
Primary Settled Wastewater and Unsettled Trickling Filter Recycle
Rotary Distributor
Speed Control
Pump
To Waste
Trickling Filter
Pilot Plant Influent
Filter Effluent
Baffle
Primary Effluent
Recycle
Baffle
Pilot Plant Effluent
Primary Clarifier
Final Settling Tank
Valve
Sludge
Sludge

FIGURE 16. FLOW DIAGRAM OF TRICKLING FILTER PILOT PLANT FOR SINGLE-STAGE FILTRATION.

Chemicals for phosphorus precipitation may be added at one or more of several points in a treatment sequence (3, 6, 9). Prior to this study, the relative effectiveness of different points of addition in a conventional trickling filter plant had not been evaluated simultaneously. To perform such a study, all four trickling filter pilot plant systems had to be employed. This was justifiable since previously all four pilot plant systems were found to provide comparable performance under identical loading conditions.

Three studies with alum doses of 100, 150, and 200 mg/l were conducted utilizing the above four units. The experimental design in each study was as follows:

System TF-1	Control - no alum addition
System TF-2	Alum addition to cone at which influent entered primary clarifier
System TF-3	Alum addition to dosing chamber of trickling filter
System TF-4	Alum addition to cone (recirculation funnel) at which filter effluent passed to the secondary clarifier, just above point of recirculation (simulating split-addition)

Alum addition was accomplished by pumping a concentrated stock alum solution at a constant rate to the desired input point with a manifolded Harvard pump. The design of the pilot units assured turbulence and thorough mixing at the various points of addition.

Alum $[Al_2(SO_4)_3 \cdot 18\ H_2O]$ doses were calculated on the basis of influent flow to the units, without consideration of the recycle flow. Therefore, in each instance the actual alum concentration was 1/3 of the stated feed concentration. In the following discussion, the alum concentration will be referred to in terms of the nominal dose, i.e., the dose calculated on the basis of influent flow only.

The results of these pilot studies are summarized in Tables 22 to 24. Data collected on days in which unusual operational difficulties were encountered are not included in these summaries.

Analysis of Tables 22 to 24 indicates that alum addition to the primary clarifier is more effective than addition to the trickling filter and as good or better than split-addition to the primary and secondary clarifiers.

In a follow-up pilot-scale study, two of the four trickling filter systems were employed with a constant alum dosage of 200 mg/l. One system (TF-4) was modified to permit alum addition into the secondary clarifier below the point of recycle withdrawal; the point of alum addition in the other system (TF-3) was the primary clarifier. The results of this follow-up study are shown in Table 25.

The two systems exhibited little difference in overall TSS removal efficiency, 77 percent in System TF-3 compared to 75 percent in System TF-4. Examination of the data indicates a dramatic decrease in TSS concentration in the effluents from the individual process units to which alum was added, but little overall difference in the final effluents. Average TSS solids removal of 77 and 78

TABLE 22

COMPARISON OF ALuM ADDITION (100 mg/l) TO PRIMARY CLARIFIER INFLUENT, TRICKLING FILTER INFLUENT, AND SECONDARY CLARIFIER INFLUENT AHEAD OF RECIRCULATION

		Control - No Alum Addition				$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added to Pri. Clar. Inf.			$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added to Tr. Filt. Inf.			$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added to Sec. Clar. Inf.		
		Inf	P-1	F-1	S-1	P-2	F-2	S-2	P-3	F-3	S-3	P-4	F-4	S-4
BOD_5(Tot)	Ave, mg/l	134	43	35	24	98	44	35	99	53	41	42	32	40
	Max, mg/l	144	65	68	30	171	53	43	183	63	63	45	33	53
	Min, mg/l	114	26	52	20	45	38	29	41	42	30	38	31	13
	% Removal		68	74	82	27	67	74	26	60	69	69	76	70
TOC	Ave, mg/l	114	54	46	32	86	49	36	87	52	48	93	61	47
	Max, mg/l	122	73	65	40	218	72	45	226	74	66	184	122	69
	Min, mg/l	103	46	34	18	38	39	28	44	38	32	55	41	34
	% Removal		53	60	72	25	57	68	24	54	58	18	46	59
TSS	Ave, mg/l	170	56	57	30	171	94	44	137	99	57	152	108	64
	Max, mg/l	273	87	86	81	528	148	77	477	201	110	340	192	131
	Min, mg/l	122	37	36	12	69	56	25	49	57	16	67	67	23
	% Removal		67	66	82	0	45	74	19	42	66	11	36	62
VSS	Ave, mg/l	146	46	49	25	125	63	33	109	69	39	100	78	44
	Max, mg/l	239	63	78	63	388	92	66	365	153	70	277	123	96
	Min, mg/l	104	32	31	9	61	41	18	36	49	16	55	53	19
	% Removal		68	66	83	14	57	77	25	53	73	32	47	70
TS	Ave, mg/l	454	--	--	291	--	--	309	--	--	347	--	--	346
	Max, mg/l	494	--	--	367	--	--	413	--	--	410	--	--	379
	Min, mg/l	398	--	--	260	--	--	131	--	--	314	--	--	302
	% Removal		--	--	36	--	--	32	--	--	24	--	--	24
TIP	Ave, mg/l	7.5	7.7	7.5	7.3	5.3	5.6	4.0	6.6	5.4	5.0	6.7	5.3	5.2
	Max, mg/l	9.7	9.6	9.0	9.1	8.9	12.9	6.2	11.4	8.5	8.0	9.7	11.9	7.8
	Min, mg/l	6.4	6.4	2.4	2.0	1.7	2.0	2.1	3.9	2.3	2.2	3.6	2.2	2.1
	% Removal		0	0	3	29	25	47	12	28	33	11	29	31
TP	Ave, mg/l	9.7	8.7	9.1	8.1	9.1	7.9	5.5	8.8	7.6	7.3	10.1	7.7	6.9
	Max, mg/l	10.7	10.3	10.0	10.4	14.6	15.2	7.6	15.5	11.2	9.6	15.1	15.2	9.6
	Min, mg/l	7.7	7.3	7.9	5.1	3.7	3.1	2.2	5.2	3.9	4.7	7.1	4.5	2.9
	% Removal		10	6	16	6	19	43	9	22	25	0	21	29

Legend: P - Primary Clarifier Effluent; F- Trickling Filter Effluent
S - Secondary Clarifier Effluent; 1, 2, 3, and 4 - System Numbers

TABLE 22 (continued)

COMPARISON OF ALUM ADDITION (100 mg/l) TO PRIMARY CLARIFIER INFLUENT, TRICKLING FILTER INFLUENT, AND SECONDARY CLARIFIER INFLUENT AHEAD OF RECIRCULATION

		Control - No Alum Addition				$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added to Pri. Clar. Inf.			$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added to Tr. Filt. Inf.			$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added to Sec. Clar. Inf.		
		Inf.	P-1	F-1	S-1	P-2	F-2	S-2	P-3	F-3	S-3	P-4	F-4	S-4
NO_2-N	Ave, mg/l	0.05	0.17	0.12	0.16	0.09	0.15	0.14	0.06	0.12	0.17	0.04	0.06	0.07
	Max, mg/l	0.17	0.48	0.26	0.38	0.17	0.34	0.30	0.22	0.21	0.35	0.11	0.15	0.16
	Min, mg/l	>0.01	0.07	0.07	0.08	0.02	0.08	0.05	0.01	0.06	0.09	0.02	0.01	0.03
NO_3-N	Ave, mg/l	0.1	0.4	0.8	0.7	0.4	1.2	0.8	0.1	0.4	0.4	0.6	0.7	0.6
	Max, mg/l	0.3	1.8	2.7	2.1	1.6	3.4	2.1	0.3	1.0	0.7	4.3	5.5	5.3
	Min, mg/l	>0.1	0.1	0.3	0.1	>0.1	0.1	0.1	>0.1	>0.1	0.1	0.1	0.1	0.1
NH_4^+-N	Ave, mg/l	19.3	17.4	18.1	17.0	17.5	18.7	17.5	19.3	19.3	19.7	20.3	19.8	20.0
	Max, mg/l	31.0	31.0	34.0	36.0	32.5	29.5	26.0	32.5	29.0	37.0	29.5	35.0	37.0
	Min, mg/l	13.0	11.0	12.5	9.5	10.0	9.5	9.0	14.0	12.5	13.0	13.5	13.5	13.0
Kjeld-N	Ave, mg/l	28.7	23.7	23.5	18.9	26.1	21.5	21.5	27.2	24.3	24.3	28.2	27.8	23.8
	Max, mg/l	34.0	31.5	27.5	26.5	37.0	32.5	30.5	33.0	35.0	30.5	34.0	34.5	30.0
	Min, mg/l	22.5	17.5	19.5	15.5	20.0	15.5	14.0	22.0	21.0	21.0	23.5	21.5	18.0
pH	Ave, mg/l	7.1	7.2	7.3	7.3	7.0	7.2	7.2	7.1	7.1	7.2	7.0	7.1	7.1
	Max, mg/l	7.3	7.4	7.4	7.5	7.2	7.3	7.4	7.2	7.2	7.3	7.2	7.2	7.3
	Min, mg/l	6.8	6.8	7.1	7.0	6.8	6.9	7.0	6.8	6.8	6.9	6.8	6.8	6.7
Al	Ave, mg/l	0.6	0.4	0.4	0.8	7.9	6.0	4.5	5.0	5.9	5.2	5.3	5.6	5.9
	Max, mg/l	1.3	1.0	0.9	5.2	12.0	8.6	6.4	9.5	10.1	8.0	8.0	8.0	7.0
	Min, mg/l	0.1	0.1	0.1	0.1	3.3	0.3	3.2	3.2	4.6	2.0	0.8	0.9	3.5

Legend: P - Primary Clarifier Effluent; F- Trickling Filter Effluent
S - Secondary Clarifier Effluent; 1, 2, 3, and 4 - System Numbers

TABLE 23

COMPARISON OF ALUM ADDITION (150 mg/l) TO PRIMARY CLARIFIER INFLUENT, TRICKLING FILTER INFLUENT, AND SECONDARY CLARIFIER INFLUENT AHEAD OF RECIRCULATION TAKEOFF POINT

		Control - No Alum Addition				$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added to Pri. Clar. Inf.			$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added to Tr. Filt. Inf.			$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added to Sec. Clar. Inf.		
		Inf	P-1	F-1	S-1	P-2	F-2	S-2	P-3	F-3	S-3	P-4	F-4	S-4
BOD_5(Tot)	Ave, mg/l	116	61	39	58	49	26	33	69	49	30	82	46	35
	Max, mg/l	120	118	50	138	120	34	48	120	89	45	118	60	56
	Min, mg/l	114	23	35	24	29	20	10	44	24	23	50	34	18
	% Removal		47	64	50	58	78	72	41	58	74	29	60	70
TOC	Ave, mg/l	122	82	45	52	77	34	30	78	52	42	87	47	31
	Max, mg/l	152	185	75	114	235	52	39	216	64	72	221	73	56
	Min, mg/l	80	32	17	25	24	12	13	22	40	28	27	8	9
	% Removal		33	63	57	37	72	75	36	57	66	29	61	75
TSS	Ave, mg/l	146	102	40	43	129	71	46	128	97	68	162	97	69
	Max, mg/l	200	265	87	154	523	130	84	387	139	158	335	154	205
	Min, mg/l	100	36	25	11	47	30	19	39	71	36	64	65	27
	% Removal		30	73	70	12	51	68	12	34	53	---	34	53
VSS	Ave, mg/l	113	75	32	38	87	48	28	95	62	50	123	65	45
	Max, mg/l	158	154	66	138	362	71	56	302	75	123	249	96	145
	Min, mg/l	71	26	16	5	35	16	14	34	54	29	31	39	20
	% Removal		34	72	64	23	58	75	84	45	56	---	42	60
TS	Ave, mg/l	433	---	---	327	---	---	325	---	---	362	---	---	359
	Max, mg/l	487	---	---	463	---	---	372	---	---	524	---	---	502
	Min, mg/l	389	---	---	262	---	---	284	---	---	287	---	---	289
	% Removal		---	---	24	---	---	24	---	---	16	---	---	17
TIP	Ave, mg/l	6.9	7.4	7.4	7.1	6.1	4.6	4.2	5.7	5.4	4.8	5.7	4.6	4.1
	Max, mg/l	9.0	9.6	8.8	10.0	17.9	8.7	6.1	9.8	6.5	6.5	9.3	7.1	5.7
	Min, mg/l	4.9	5.2	6.0	4.9	1.5	1.7	2.3	2.5	2.4	2.9	2.3	1.8	2.4
	% Removal		----	-----	-----	12	33	39	17	22	29	17	33	39
TP	Ave, mg/l	9.2	9.3	8.7	8.9	6.9	7.3	5.6	7.8	10.3	7.2	7.8	7.0	5.4
	Max, mg/l	12.0	13.3	11.8	13.2	16.8	12.5	9.4	12.2	15.8	16.2	11.4	10.0	9.0
	Min, mg/l	7.3	7.4	5.5	6.9	3.6	4.2	3.1	4.2	7.5	4.5	4.0	3.8	3.9
	% Removal			5	3	25	21	39	15		21	15	14	14

Legend: P - Primary Clarifier Effluent; F - Trickling Filter Effluent
S - Secondary Clarifier Effluent; 1, 2, 3, and 4 - System Numbers

TABLE 23 (continued)

COMPARISON OF ALUM ADDITION (150 mg/l) TO PRIMARY CLARIFIER INFLUENT, TRICKLING FILTER INFLUENT, AND SECONDARY CLARIFIER INFLUENT AHEAD OF RECIRCULATION TAKEOFF POINT

		Control - No Alum Addition				$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added			$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added			$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added		
						to Pri. Clar. Inf.			to Tr. Filt. Inf.			to Sec. Clar. Inf.		
		Inf	P-1	F-1	S-1	P-2	F-2	S-2	P-3	F-3	S-3	P-4	F-4	S-4
NO_2-N	Ave, mg/l	0.06	0.17	0.14	0.16	0.07	0.12	0.09	0.07	0.10	0.12	0.05	0.17	0.17
	Max, mg/l	0.30	0.34	0.28	0.28	0.23	0.20	0.17	0.17	0.15	0.23	0.10	0.47	0.34
	Min, mg/l	0.01	0.03	0.09	0.04	0.01	0.07	0.04	0.02	0.03	0.06	0.02	0.06	0.05
NO_3-N	Ave, mg/l	0.5	0.4	0.7	0.7	0.6	2.0	1.9	0.2	0.7	0.6	0.6	0.9	0.7
	Max, mg/l	2.3	0.7	1.2	1.6	0.8	4.4	3.8	0.5	1.2	0.9	1.1	2.2	1.4
	Min, mg/l	0.1	0.1	0.3	0.3	0.1	0.4	0.7	0.1	0.2	0.3	0.3	0.3	0.4
NH_4^+-N	Ave, mg/l	21.3	19.6	18.5	18.3	19.3	17.4	17.2	20.4	20.5	20.1	19.8	18.7	19.5
	Max, mg/l	33.0	35.5	32.0	34.5	31.0	28.0	30.0	32.5	31.5	32.0	31.5	28.5	33.5
	Min, mg/l	13.5	13.5	13.5	12.0	12.0	11.0	11.0	14.0	13.5	14.0	12.0	12.5	12.5
Kjeld-N	Ave, mg/l	24.7	23.7	20.4	20.7	21.4	19.1	18.6	23.0	22.9	21.6	24.0	22.3	21.0
	Max, mg/l	39.5	42.0	34.5	36.5	31.0	28.5	30.0	32.5	36.0	35.0	41.5	34.0	38.0
	Min, mg/l	15.0	15.0	14.5	14.5	14.5	15.0	14.0	17.5	16.5	17.0	15.0	15.5	14.3
pH	Ave, mg/l	7.0	7.1	7.2	7.1	6.9	7.0	7.1	7.0	7.0	7.0	6.8	6.8	6.8
	Max, mg/l	7.5	7.5	7.7	7.7	7.1	7.3	7.3	7.4	7.2	7.4	7.3	7.0	7.2
	Min	6.6	6.8	6.8	6.9	6.6	6.7	6.7	6.5	6.7	6.6	6.4	6.3	6.4
Al	Ave, mg/l	0.9	0.7	0.5	1.2	10.5	7.7	5.8	7.4	10.3	6.8	7.4	8.9	7.4
	Max, mg/l	2.5	1.4	0.8	7.5	32.0	13.2	9.4	30.2	25.0	14.1	15.3	12.8	13.7
	Min, mg/l	0.1	0.1	0.1	0.1	0.6	1.0	1.7	1.5	1.9	1.6	2.5	2.5	2.1

Legend: P - Primary Clarifier Effluent; F - Trickling Filter Effluent
S - Secondary Clarifier Effluent; 1, 2, 3, and 4 - System Numbers

TABLE 24

COMPARISON OF ALUM ADDITION (200 mg/l) TO PRIMARY CLARIFIER INFLUENT, TRICKLING FILTER INFLUENT, AND SECONDARY CLARIFIER INFLUENT AHEAD OF RECIRCULATION TAKEOFF POINT

		Control - No Alum Addition				$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added to Pri. Clar. Inf.			$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added to Tr. Filt. Inf.			$Al_2(SO_4)_3$ 18 H_2O Added to Sec. Clar. Inf.		
		Inf	P-1	F-1	S-1	P-2	F-2	S-2	P-3	F-3	S-3	P-4	F-4	S-4
BOD_5(Tot)	Ave, mg/l	163	73	32	18	51	26	11	87	35	31	71	37	12
	Max, mg/l	174	135	39	19	77	50	18	89	43	41	108	44	18
	Min, mg/l	156	39	25	16	23	6	2	84	24	11	27	27	6
	% Removal		55	80	89	69	84	93	47	78	81	56	77	93
TOC	Ave, mg/l	112	65	38	39	51	27	18	54	38	34	56	42	33
	Max, mg/l	152	160	47	67	85	38	29	88	58	70	132	65	58
	Min, mg/l	55	29	28	27	16	10	10	31	15	11	14	28	12
	% Removal		29	66	65	54	76	84	52	66	70	50	62	70
TSS	Ave, mg/l	118	61	29	35	91	43	20	72	77	54	74	91	74
	Max, mg/l	171	163	44	180	276	94	34	128	157	166	143	149	126
	Min, mg/l	72	24	15	5	11	20	4	24	32	26	35	31	32
	% Removal		48	79	70	23	64	83	42	35	54	37	23	37
VSS	Ave, mg/l	100	51	23	29	69	33	15	54	55	39	57	59	41
	Max, mg/l	154	128	33	179	196	58	25	92	138	104	112	95	59
	Min, mg/l	31	11	12	2	8	17	2	19	28	15	17	18	20
	% Removal		49	77	71	31	67	85	46	45	61	43	41	59
TS	Ave, mg/l	447	---	--	313	---	--	325	---	---	352	---	---	375
	Max, mg/l	533	---	--	397	---	--	467	---	---	480	---	---	520
	Min, mg/l	296	---	--	247	---	--	239	---	---	299	---	---	288
	% Removal		---	--	30	---	--	27	---	---	21	---	---	16
TIP	Ave, mg/l	6.7	6.6	6.7	6.7	4.0	2.6	2.4	4.6	4.6	3.9	3.9	4.4	3.5
	Max, mg/l	8.9	7.8	8.7	8.1	7.0	6.9	6.3	8.3	11.5	8.0	10.3	6.9	10.2
	Min, mg/l	2.8	3.8	4.3	4.3	<0.5	<0.5	<0.5	1.0	0.7	<0.5	<0.5	0.9	<0.5
	% Removal		2	0	0	40	61	64	31	31	42	42	34	48
TP	Ave, mg/l	9.7	8.9	9.0	8.7	5.6	3.8	3.1	7.1	7.6	6.5	6.0	6.9	5.1
	Max, mg/l	14.4	11.7	14.6	11.4	10.0	10.5	9.0	16.3	21.0	19.0	15.5	9.8	13.5
	Min, mg/l	4.0	4.7	5.7	5.4	<0.5	<0.5	<0.5	1.9	2.6	<0.5	<0.5	2.2	<0.5
	% Removal		8	7	10	42	61	68	27	22	33	30	29	47

Legend: P - Primary Clarifier Effluent; F - Trickling Filter Effluent
S - Secondary Clarifier Effluent; 1, 2, 3, and 4 - Systems Numbers

TABLE 24 (continued)

COMPARISON OF ALUM ADDITION (200 mg/l) TO PRIMARY CLARIFIER INFLUENT, TRICKLING FILTER INFLUENT, AND SECONDARY CLARIFIER INFLUENT AHEAD OF RECIRCULATION TAKEOFF POINT

		Control - No Alum Addition				$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added to Pri. Clar. Inf.			$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added to Tri. Filt. Inf.			$Al_2(SO_4)_3 \cdot 18\ H_2O$ Added to Sec. Clar. Inf.		
		Inf.	P-1	F-1	S-1	P-2	F-2	S-2	P-3	F-3	S-3	P-4	F-4	S-4
NO_2-N	Ave, mg/l	0.03	---	---	0.14	---	---	0.38	---	---	0.07	---	---	0.10
	Max, mg/l	0.05	---	---	0.22	---	---	1.20	---	---	0.13	---	---	0.18
	Min, mg/l	<0.01	---	---	0.07	---	---	<0.01	---	---	0.04	---	---	0.02
NO_3-N	Ave, mg/l	0.15	---	---	2.0	---	---	1.1	---	---	0.8	---	---	0.6
	Max, mg/l	0.20	---	---	4.2	---	---	2.6	---	---	0.9	---	---	1.1
	Min, mg/l	<0.10	---	---	0.6	---	---	0.5	---	---	0.6	---	---	0.5
NH_4^+-N	Ave, mg/l	21.1	---	---	15.1	---	---	18.3	---	---	20.2	---	---	19.2
	Max, mg/l	28.5	---	---	22.0	---	---	26.0	---	---	26.5	---	---	25.0
	Min, mg/l	14.0	---	---	8.0	---	---	13.0	---	---	16.0	---	---	15.5
Kjeld-N	Ave, mg/l	26.2	---	---	18.3	---	---	19.8	---	---	21.6	---	---	21.1
	Max, mg/l	33.0	---	---	23.0	---	---	26.0	---	---	27.0	---	---	26.0
	Min, mg/l	17.0	---	---	12.0	---	---	16.5	---	---	17.5	---	---	17.0
	% Removal				30			24			18			19
pH	Ave, mg/l	6.9	7.1	7.2	7.2	6.5	6.7	6.9	6.9	6.8	6.8	6.6	6.4	6.6
	Max, mg/l	7.3	7.3	7.3	7.4	7.3	7.3	7.4	7.1	7.2	7.3	7.2	7.3	7.0
	Min, mg/l	6.6	6.6	6.8	6.8	4.9	5.1	5.9	6.0	5.7	5.9	5.0	4.5	5.2
Al	Ave, mg/l	1.2	0.8	0.7	0.6	5.8	4.6	3.0	4.8	8.8	7.0	6.6	11.4	7.2
	Max, mg/l	2.7	2.0	1.4	1.7	11.0	7.5	4.8	7.0	14.8	19.3	17.4	15.8	13.8
	Min, mg/l	0.7	0.4	0.3	0.1	2.6	2.0	1.0	2.8	4.5	1.9	2.7	7.0	3.2

Legend: P - Primary Clarifier Effluent; F - Trickling Filter Effluent
S - Secondary Clarifier Effluent; 1, 2, 3, and 4 - System Numbers

TABLE 25

COMPARISON OF ALUM ADDITION (200 mg/l) TO PRIMARY CLARIFIER INFLUENT AND SECONDARY INFLUENT AFTER RECIRCULATION TAKEOFF POINT

Without Alum Addition	TSS, mg/l							BOD_5, mg/l							TOC, mg/l							Total System TP Removal, %	
	Inf	P-3	F-3	S-3	P-4	F-4	S-4	Inf	P-3	F-3	S-3	P-4	F-4	S-4	Inf	P-3	F-3	S-3	P-4	F-4	S-4	3	4
2/13/72	138	46	56	27	30	89	14	---	---	---	---	---	---	---	93	43	46	38	46	65	29	0	8
2/15/72	116	107	63	33	33	68	13	---	---	---	---	---	---	---	---	---	---	---	---	---	---	30	26
2/17/72	116	62	65	23	76	119	51	204	71	62	39	77	159	50	---	---	---	---	---	---	---	16	12
Ave	123	72	61	28	46	92	26	204	71	62	39	77	159	50	93	43	46	38	46	65	29	15	15
With Alum Addition *																							
2/22/72	195	52	45	52	152	84	22	126	27	29	29	114	68	15	152	35	35	32	127	85	23	70	76
2/24/72	177	51	51	123	48	96	72	---	---	---	---	---	---	---	145	48	38	54	61	65	33	50	55
2/26/72	164	33	57	29	138	132	25	---	---	---	---	---	---	---	125	32	38	21	112	99	26	77	75
2/29/72	169	44	75	38	146	36	49	150	36	42	27	78	112	23	140	41	43	37	98	115	30	67	68
3/2/72	203	38	57	24	332	271	82	---	---	---	---	---	---	---	130	33	40	30	195	131	35	79	69
3/5/72	194	27	51	12	106	148	40	---	---	---	---	---	---	---	139	28	32	21	107	102	28	85	69
3/7/72	289	147	94	25	70	254	45	204	39	38	23	84	117	21	193	42	42	28	86	121	26	72	73
3/9/72	160	126	123	34	96	281	38	---	---	---	---	---	---	---	151	56	49	28	101	141	25	77	80
Ave	193	61	69	42	136	163	47	160	34	36	26	92	99	20	147	39	40	31	105	107	28	72	70

Legend: P - Primary Clarifier Effluent; F - Trickling Filter Effluent
S - Secondary Clarifier Effluent; 3 and 4 - System Numbers

* On System 3, 200 mg/l $Al_2(SO_4)_3 \cdot 18\ H_2O$ added to primary clarifier influent.
On System 4, 200 mg/l $AL_2(SO_4)_3 \cdot 18\ H_2O$ added to secondary clarifier influent after recirculation takeoff point.

percent were achieved in the week just prior to the alum study. Therefore, it must be concluded that under the conditions of this pilot study, TSS removals were not enhanced by alum precipitation.

Visual observation, however, indicated that the character of effluent TSS during alum addition differed from that when no alum was added. Alum floc was visible during alum addition and probably contributed to the effluent TSS.

TOC removal was slightly better (80 percent) in System TF-4 than in System TF-3 (73 percent). Likewise, BOD_5 removal was slightly better in System TF-4 (87 percent, compared to 83 percent). Again, examination of the data shows a dramatic decrease of BOD_5 and TOC in the effluents of the individual process units to which alum was added, but little overall difference in total plant efficiency. Insufficient data were available from the time period immediately prior to this study to make a valid comparison of BOD_5 and TOC removals with and without alum addition.

Phosphorus removal efficiency of the two systems was about the same, 72 percent in System TF-3 compared to 70 percent in System TF-4.

From these pilot-scale investigations, the following conclusions were reached:

(1) Alum addition substantially improved phosphorus removal,
(2) Increased alum dosages up to 200 mg/l (the highest dose tested) resulted in increased phosphorus removal,
(3) Alum addition to trickling filter influent or to trickling filter effluent above the takeoff point of recirculation was less effective for phosphorus removal than was addition to primary clarifier influent or to influent to the secondary clarifier below the takeoff point of recirculation, and
(4) Overall removals of BOD_5, TOC, and phosphorus were essentially the same when alum was dosed to primary clarifier influent or to influent to the secondary clarifier below the takeoff point of recirculation.

SECTION V

ALUM ADDITION TO CHAPEL HILL MAIN PLANT

On the basis of laboratory and pilot-scale results, the addition of metal salts to trickling filter effluent appeared to offer a technically feasible alternative of upgrading overall trickling filter plant performance. This was confirmed by a preliminary report (18) of full-scale treatment with liquid alum at Richardson, Texas. The Richardson results indicated that the addition of alum to trickling filter effluent just prior to final clarification was effective in removing phosphorus and enhancing general plant performance. An initial trial adding alum ahead of primary clarification at Richardson resulted in apparent overloading and impending failure of the plant's unheated anaerobic digesters, necessitating termination of that trial. Split addition of alum with 20 percent to the primary clarifier and 80 percent to the final clarifier produced very efficient phosphorus removal. However, when the split was altered with 30 percent to the primary clarifier and 70 percent to the final clarifier, early but unmistakable signs of digester problems again developed. In a final trial, alum addition ahead of the final clarifier provided good phosphorus removal with no indications of impending digester upset. This point of alum application was adopted for extended study at Richardson.

The addition of alum to pilot trickling filter plants at Chapel Hill, as described previously in this report, indicated that approximately equal results could be obtained with the addition of alum to either primary or final clarifiers. However, primarily because of the preliminary work at Richardson, Texas, it was decided to apply alum in the Chapel Hill main plant at a point just ahead of final settling in one of the plant's two trains. No alum was added to the other train. Therefore, when the plant flow was equally divided, overall performance of the two trains could be compared on the basis of phosphorus removal or any other parameter of interest.

There were a number of reasons for attempting to confirm the promising results obtained at Richardson, Texas at the plant in Chapel Hill. The principal considerations in this regard were the following:

1. The Richardson plant is a standard-rate trickling filter facility, whereas the Chapel Hill plant is a high-rate facility.

2. Except for secondary sludge return to the primary settling tanks, no recirculation is provided at Richardson. At Chapel Hill, trickling filter effluent is recirculated through the primary settling tanks.

3. Only one final settling tank exists at the Richardson plant, and it is, therefore, impossible to simultaneously compare the results of normal operation with chemical treatment. On the other hand, it is possible to operate the two trains of the Chapel Hill plant as if they are two separate facilities. With this flexibility, many direct comparisons are possible between normal operation and operation with chemical addition.

4. The single final settling tank at Richardson was quite large relative to normal design practice. The surface loading on this tank at the design flow of 5,678 m^3/day (1.5 mgd) is 16.7 m^3/day/m^2 (410 gpd/ft^2). The average surface loading on the Chapel Hill final tanks is about 36.7 m^3/day/m^2 (900 gpd/ft^2), which is more typical of final tanks at many high-rate trickling filter plants.

5. At Richardson, secondary sludge is returned to three primary settling units which consist of two-story tanks; the upper levels are clarifiers and the bottom sections are unheated digesters. Since the combined primary and secondary sludges drop directly through the primary clarifiers into the digesters below, it is impossible to measure the actual quantity of sludge produced. At Chapel Hill, all sludge, both primary and returned secondary, is accumulated in the two primary settling tanks and pumped independently from each train to one separate anaerobic digestion facility. Accordingly, it is possible to measure the quantity of sludge produced on each side of the plant. The quantity of sludge resulting from chemical treatment is one of the most important factors in designing solids treatment and disposal systems.

THE CHAPEL HILL TREATMENT PLANT

The wastewater treatment plant for Chapel Hill is a conventional high-rate trickling filter installation treating predominantly domestic wastewater. There is substantially no industrial or other unusual contribution, except for the hospital and laboratories of the University of North Carolina. Figure 17 is a partial flow sheet for the plant, and Table 26 summarizes characteristics and design parameters of major plant units.

Incoming wastewater passes through a mechanically cleaned bar screen, with a manual unit serving as a backup in case of failure. Subsequently, the flow is metered and grit removed in a detritor. Design of the grit removal effluent structure allows splitting of flow into any desired proportions for diversion to the two identical treatment trains.

Based on a total plant influent flow of 11,355 m^3/day (3.0 mgd), equally divided between two trains, and a recycle ratio of 2:1, the 21.3-m (70-ft) primary clarifiers provide 1.8 hr detention time at an overflow rate of 48 m^3/day/m^2 (1,180 gpd/ft^2). Each trickling filter is 36.6 m (120 ft) in diameter with a stone depth of 1.3 m (4.25 ft), providing a "design" loading of about 0.56 kg/day/m^3 (35

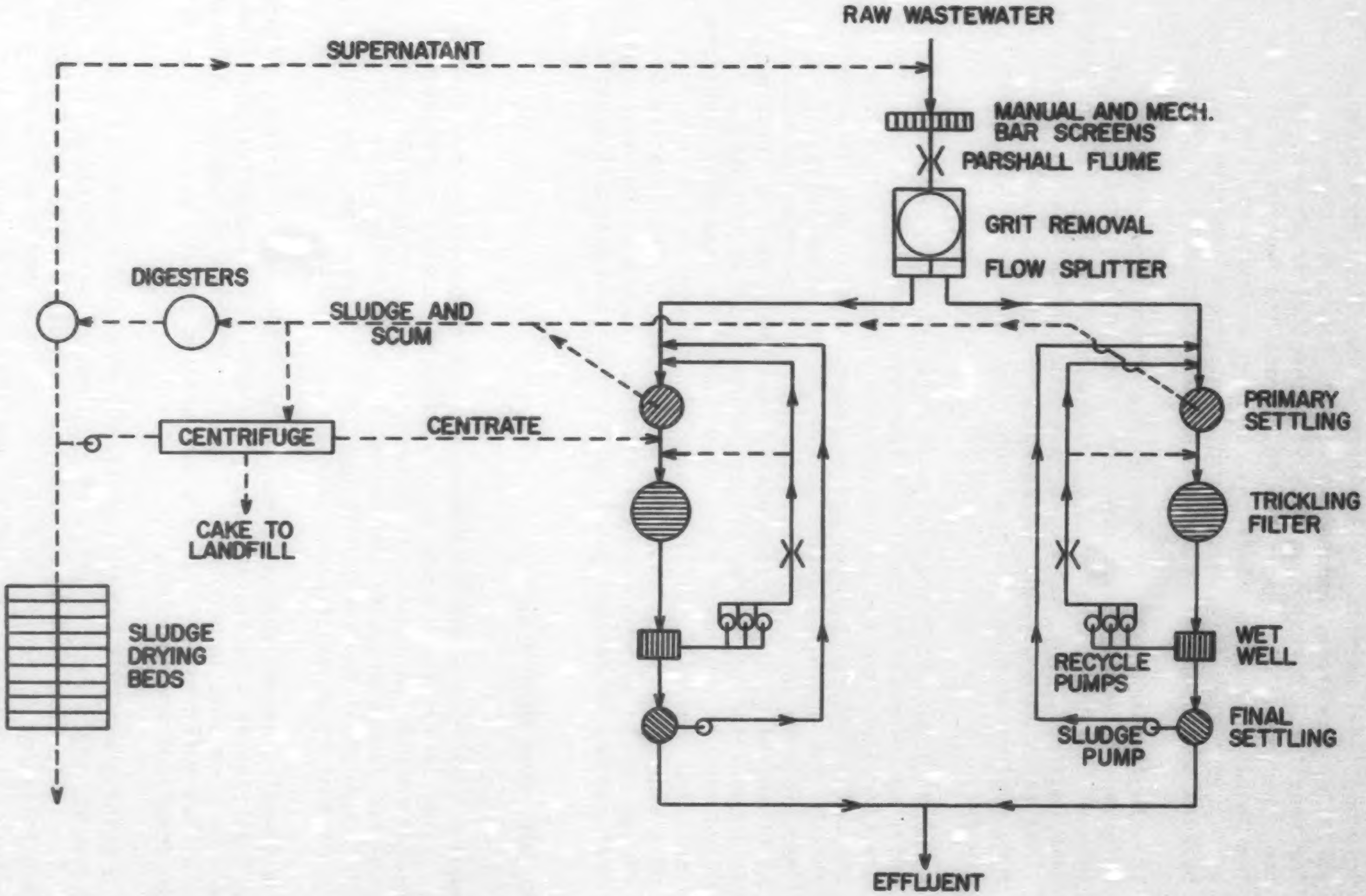

RAW WASTEWATER
SUPERNATANT
MANUAL AND MECH. BAR SCREENS
PARSHALL FLUME
GRIT REMOVAL
FLOW SPLITTER
DIGESTERS
SLUDGE AND SCUM
CENTRIFUGE
CENTRATE
CAKE TO LANDFILL
SLUDGE DRYING BEDS
PRIMARY SETTLING
TRICKLING FILTER
WET WELL
RECYCLE PUMPS
FINAL SETTLING
SLUDGE PUMP
EFFLUENT

FIGURE 17. PARTIAL FLOW SHEET FOR CHAPEL HILL WASTEWATER TREATMENT PLANT

TABLE 26
CHARACTERISTICS OF AND DESIGN PARAMETERS FOR UNITS IN CHAPEL HILL WASTEWATER TREATMENT PLANT

CURRENT AVERAGE FLOW:

Approximately 3.0 mgd

SCREENS:

a) One automatic, mechanically-cleaned
b) One manually-cleaned (standby)

GRIT REMOVAL:

One mechanically-cleaned detritor

PRIMARY SETTLING (Two units):

a) Diameter = 70 ft
b) Water depth = 12 ft
c) Detention time = 1.8 hr (@ 2:1 Recycle)
d) Overflow rate = 1,180 gpd/ft^2 (@ 2:1 Recycle)
e) Mechanical sludge and scum removal

TRICKLING FILTERS (Two units):

a) Diameter = 120 ft
b) Stone depth = 4.25 ft
c) Rotary distributors
d) BOD_5 loading about 35 lb/day/1000 ft^3 (assuming 1/3 removal during primary treatment)
e) Hydraulic loading = 17 mgad (@ 2:1 Recycle)

FINAL SETTLING (Two units):

a) Diameter = 45 ft
b) Water depth = 10 ft
c) Detention time = 1.9 hr
d) Overflow rate = 960 gpd/ft^2
e) Mechanical sludge removal

RECIRCULATION PUMPS:

In each battery, one 1.5 mgd and two 3.0 mgd units

ANAEROBIC DIGESTERS:

a) One 75 ft diameter, mechanically mixed, heated, floating cover (primary digester)
b) One 50 ft diameter, mechanically mixed, heated, floating cover (secondary digester)
c) One 50 ft diameter, no mixing, floating cover (not now in operation)
d) Heat exchanger (digester gas or propane) for units in operation now, including pumps, control valves, and interconnecting piping

SLUDGE DEWATERING:

a) 18 sand drying beds, 25 ft x 50 ft, uncovered
b) One 18-in solid-bowl, 15-17 gpm, Bird centrifuge

Conversions:
1. 1 in = 2.54 cm
2. 1 ft = 0.3048 m
3. 1 gpd/ft^2 = 0.04074 m^3/day/m^2
4. 1 lb/day/1,000 ft^3 = 0.01602 kg/day/m^3
5. 1 gpm = 0.06308 l/sec
6. 1 mgad = 9.353 m^3/day/ha

lb BOD_5/day/1000 ft^3)(assuming one-third BOD_5 removal in the primary clarifiers) at a hydraulic loading of approximately 159,000 m^3/day/ha (17 mgad). Trickling filter effluent passes through a wet well from which any or all of three pumps take recycle at rates up to 22,710 m^3/day (6.0 mgd) in each train. Net plant flow (no recycle) passes to 13.7 m (45 ft) diameter final clarifiers, providing 1.9 hr detention time with an overflow rate of 39.1 $m^3/day/m^2$ (960 gpd/ft^2) at 5,678 m^3/day (1.5 mgd) through each train.

Normal plant operation is based on recycle to each primary clarifier influent; however, a connection has been provided to permit recycling directly around each trickling filter. Series or stage operation of the filters is not possible. Typically, the plant operates with the two trains in parallel as shown in Figure 17, in effect providing two separate treatment facilities. The influent wastewater flow can be divided between these as desired for operation at different loadings. Recycle in each train may be adjusted independently.

Sludge from each final settling tank is returned to its respective primary clarifier where it resettles in combination with primary sludge. Sludge and scum are pumped from the primary clarifiers to a 22.9 m (75 ft) diameter first-stage or primary anaerobic digester equipped with floating cover and mixer. A 15.2 m (50 ft) diameter digester, with infrequently used mechanical mixer, serves as a second-stage digester. Supernatant from the secondary digester is slowly decanted during periods of low plant flow and is returned to the plant headworks. Gas produced in the process is utilized for heating the sludge digesters, and the excess is flared.

Digested sludge is usually dewatered with the plant's centrifuge. This machine is backstopped by 18 uncovered sand drying beds. The centrifuge also may be used for dewatering undigested sludge if unusual circumstances require reduction of loading on the sludge digesters.

PREPARATORY WORK FOR ALUM TREATMENT

As it was decided to add alum just ahead of one final clarifier, it was necessary to examine the diurnal characteristics of the trickling filter effluent entering this tank. Accordingly, a short term sampling program was conducted during December 1971 and January 1972. Around-the-clock samples were obtained of final settling tank influent. The parameter measured was total phosphorus as this was thought to be most significant in terms of alum requirements. During this sampling period, filter recirculation ratios were held at about 2.0. The recirculation almost completely suppresses the diurnal variation in concentration of normal plant influent wastewater constituents, e.g., BOD, TSS, etc. This suppression of variation in concentration was also found in the case of total phosphorus. In fact, no discernable pattern of diurnal variation in total phosphorus concentration was observed in final clarifier influent. The loading rate (mass/time) of total phosphorus to the final clarifier was found to be approximately proportional to flow. The typical total phosphorus diurnal loading pattern as determined by the sampling program is shown by the solid curve in Figure 18.

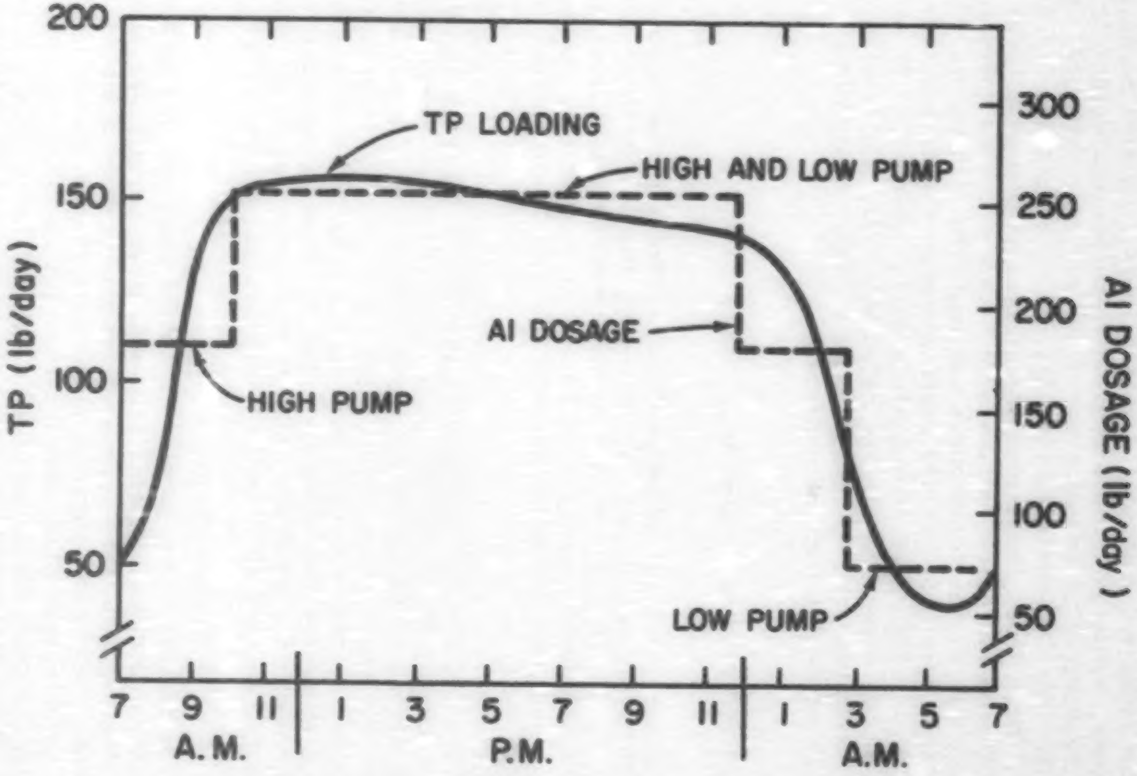


FIGURE 18. TYPICAL DIURNAL VARIATION IN TOTAL PHOSPHORUS LOADING TO FINAL CLARIFIER AND CORRESPONDING Al DOSAGE PATTERN.

With the budget remaining at the time the plant-scale alum work was started, it was not possible to purchase a flow-paced alum feeding system. However, the pumping capacity of two available Lapp chemical pumps was adjustable and an arrangement was devised using simple electrical timing devices so that the pumps could be sequenced in and out of service at selected times of the day. The initial pumping capacities of the two pumps were adjusted to 970 ml/min and 388 ml/min (15.35 gph and 6.14 gph). Using liquid alum with an Al(III) content of 4.4 percent, by weight, these pumping rates are equivalent to 82.0 kg (180.7 lb) and 32.8 kg (72.3 lb) of Al(III) per day, respectively. With both pumps operating together the resulting Al(III) feed rate was 114.8 kg/day (253 lb/day). These three feed rates were fitted to the phosphorus loading curve as illustrated by the dashed lines in Figure 18. The daily total phosphorus loading shown by the solid curve was equal to 55.8 kg/day (123 lb/day). The total daily dosage of Al(III) represented by the dashed lines was 93 kg/day (205 lb/day). Figure 18 represents a daily ratio of Al:TP on a weight basis of 1.67; on a molar basis the ratio was 1.92. Daily alum dosage could be varied by adjusting the feed rate of each pump. When this was done, both pumps were changed by the same percentage.

FACILITIES FOR ALUM TREATMENT AT CHAPEL HILL

The program of alum treatment was undertaken during the last few months of a three-year contract to explore methods of improving the operation of trickling filter treatment plants. When the alum treatment program was initiated, little money was available for new equipment. It proved to be possible, however, to locate and install equipment for handling, storing, and feeding liquid alum with minimum capital cost.

Liquid alum was stored in a 25 m^3 (6,600 gal) plastic-lined swimming pool. As liquid alum weighs about 1,318 kg/m^3 (11 lb/gal), or 32 percent more than water, the pool was never filled above the 19 m^3 (5000 gal) level. Concern about possible problems with the pool proved unjustified; no difficulties were experienced. The alum tank was set on a sand base and enclosed in a simple unheated plywood structure. This structure also enclosed the alum pumps and the pump control system. Although the ambient temperature fell as low as 10 °F during night time periods in February 1972, no crystallization problems were encountered.

Alum was fed with two positive displacement chemical feed pumps programmed to operate as previously described. Liquid alum was drawn up over the side of the storage tank with the pumps setting close to the tank, about 0.3 m (1 ft) above the tank floor. Separate discharge lines from the two pumps fed into a 3.8 cm (1 1/2 in) polyethylene pipe, and the liquid alum flowed by gravity, undiluted with water, a distance of about 18 m (60 ft) where it was discharged, in free fall, into the entrance box of the final settling tank. An elevation view of the alum feed system is shown in Figure 19.

When alum is introduced into water containing soluble phosphorus, the reaction resulting in the final formation of $Al(OH)_3$ may reduce the amount of soluble Al(III) available for the precipitation of phosphorus. On the other hand, the driving forces of the phosphate precipitation reaction indicate that if the

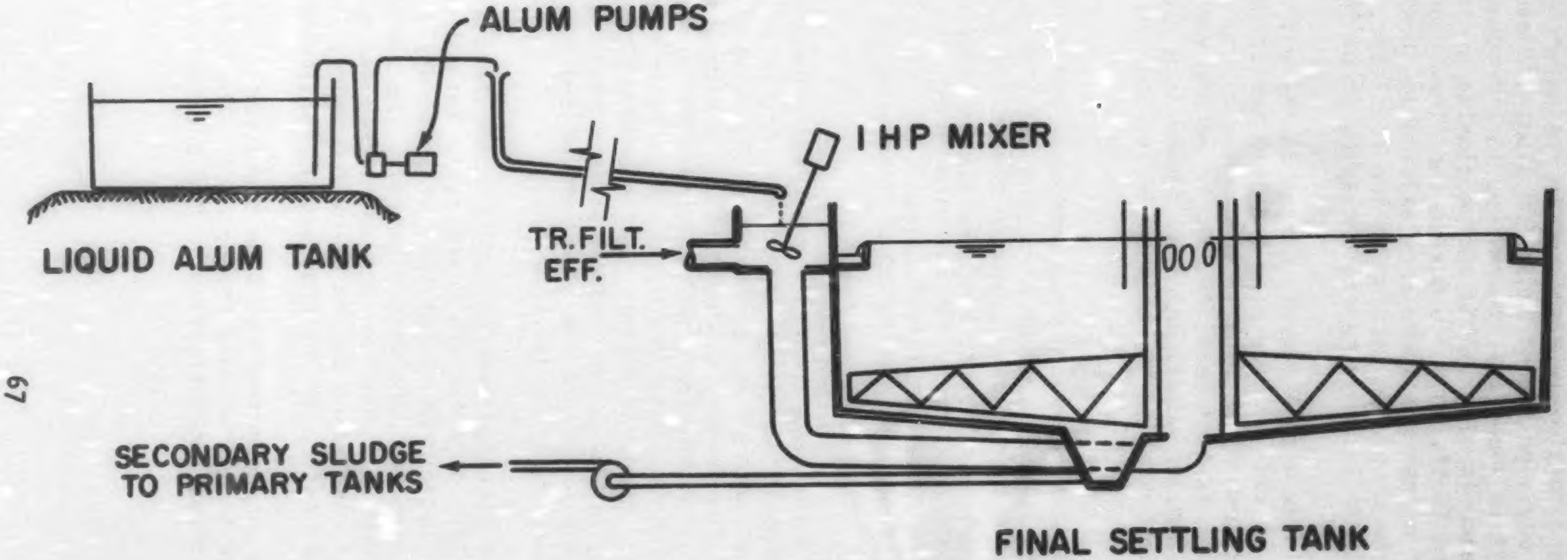

ALUM PUMPS
I H P MIXER
LIQUID ALUM TANK
TR. FILT. EFF.
SECONDARY SLUDGE TO PRIMARY TANKS
FINAL SETTLING TANK

FIGURE 19. ELEVATION VIEW OF ALUM FEEDING SYSTEM.

soluble Al(III) is rapidly and completely dispersed in the water, phosphate will be precipitated before any significant amount of aluminum reacts with the hydroxide alkalinity. It is important, therefore, to introduce the alum at a point where the turbulence is high in the entire flowing stream. A 0.75-kW (1-hp) mixer was installed in the entrance box to the final clarifier. Although a considerable amount of natural turbulence existed in this box due to the entrance of water into the drop pipe leading to the clarifier, the mixer provided additonal turbulence to insure very rapid dispersion of the alum.

After initial mixing of the alum with the waste stream in the entrance box, the wastewater flowed down a 61 cm (24 in) drop pipe and then horizontally under the settling tank to the vertical riser pipe in the center of the tank. Wastewater discharged into the tank through ports in the top of the vertical pipe inside a 76 cm (30 in) deep annular skirt, and then flowed in a radial direction from the bottom of the annular skirt to the effluent weirs located on the perimeter of the tank.

Flocculation of precipitated aluminum-phosphorus compounds and $Al(OH)_3$ complexes along with the entrained organic solids occurred in the settling tank feed pipes, in the annular section enclosed by the skirt, and in the settling tank itself. It is logical to assume that more effective flocculation could be obtained in an efficiently designed flocculation chamber. On the other hand, the simple ad hoc system described above functioned satisfactorily, i.e., well-formed floc particles were observed in the settling tank most of time when the alum dosage was above 150 mg/l.

Settled secondary sludge from the alum treatment train was returned continuously to its primary settling tank by the secondary sludge pump at a rate of 13.2 l/sec (210 gpm). The combined primary and secondary sludges were pumped from the primary settling tank to the primary digester twice each day, at 7 a.m. and 5 p.m. Secondary sludge from the train not treated with alum (i.e., the control train) was returned continuously to its primary settling tank at a rate of 12.0 l/sec (190 gpm). Combined primary and secondary sludges from the control train were separately pumped to the common primary digester. It was, therefore, possible to separately measure the flow rate of and sample the sludge pumped from each primary settling tank.

Sludges from both trains were digested anaerobically in the single 22.9 m (75 ft) diameter primary digester. This digester was mixed daily and was maintained at a temperature of 95 °F. Sludge from the primary digester was transferred daily to the 15.2 m (50 ft) diameter secondary digester. The secondary digester was neither heated or mixed; its function was to thicken the digested primary sludge prior to final dewatering and to allow the separation of a relatively clear supernatant for return to the head end of the treatment plant.

Settled sludge from the secondary digester could be dewatered in either the plant's solid-bowl centrifuge or on the sand drying beds. The centrifuge was utilized during the alum treatment investigation to the greatest extent possible.

SAMPLING AND ANALYSIS

During the alum treatment study, daily flow-weighted composite samples were obtained from all main-flow streams and the secondary sludge returns on both trains of the treatment plant using an automatic sampling system. The sampling points included in the automatic system are listed below:

Influent wastewater
Primary effluent
Trickling filter effluent
Final effluent
Secondary sludge return

The automatic sampling system was necessary as the Chapel Hill plant is not manned from 6 p.m. to 7 a.m. All waste streams sampled automatically were piped to a set of standpipes at a central location. Waste streams flowed through the standpipes continuously at a velocity sufficient to prevent the accumulation of solids. Each sample delivery pipe was equipped for back flushing. Wastewater flowing through the standpipes was continuously wasted to the recirculation well on one side of the plant. Plant influent and primary effluents were delivered to the standpipes by gravity through 3.8 cm (1 1/2 in) piping. Trickling filter effluents and secondary sludge returns were delivered through 2.5 cm (1 in) piping under the discharge pressure of the filter recirculation pumps and secondary sludge return pumps. Final effluents were delivered by means of small submersible centrifugal pumps mounted adjacent to the final tank weirs. Samples of the individual waste streams flowing through the standpipes were obtained with a rotary multitube peristaltic pump. Each pump tube of the peristaltic pump was connected to a particular standpipe. The peristaltic pump was actuated by a program timer so that the interval between sampling was approximately inversely proportional to plant flow. During the first 30 sec of sample pump operation, the lines to the sample containers were flushed to waste. Sample portions were obtained during the final second of pump operation. The flushing-sampling system was controlled by separate adjustable timers. Each final effluent sample was accumulated in a separate container stored in a cold chest and maintained at a temperature of 2-4 °C. The normal sampling day began and ended at 8 a.m. The daily flow-weighted composite samples were collected Sunday through Thursday during each week.

In addition to the above, grab samples were also obtained on a regular basis from the following points in the plant:

Sludge pumped to digester - both trains
Digested sludge in primary digester
Digested sludge in secondary digester (sludge feed to centrifuge)
Centrifuged sludge
Centrate from centrifuge
Supernatant from secondary digester

A summary of sampling points and analyses conducted is given in Table 27. The methods for chemical analyses used in this study are standard procedures listed previously in Table 5.

TABLE 27

POINTS OF SAMPLING AND ANALYSES CONDUCTED FOR MAIN-PLANT ALUM ADDITION STUDIES

Analyses \ Points	Raw W. W.	Primary Eff. 1 & 2	Tr. Filt. 1 & 2	Sec. Eff. 1 & 2	Sec. Sludge Return 1 & 2	Sludge to Digester	Digester Sup.	Digested Sludge	Centri-fuged Sludge	Centrate
BOD_5 (Tot)	A	A	A	A	B	-	-	-	-	B
TOC	A	A	A	A	A	-	B	-	-	B
TSS	A	A	A	A	A	-	B	-	-	B
VSS	B	B	B	B	B	-	B	-	-	B
TS	-	-	-	-	-	A	-	B	B	-
VS	-	-	-	-	-	A	-	B	B	-
TP	A	A	A	A	A	-	B	-	-	B
TIP	A	A	A	A	-	-	B	-	-	-
Sol. P	-	-	-	A	-	-	-	-	-	-
NH_4^+-N	B	B	B	B	-	-	B	-	-	-
Kjeld-N	B	B	B	B	-	-	B	-	-	-
NO_3-N	B	B	B	B	-	-	-	-	-	-
Turbidity	A	A	A	A	-	-	-	-	-	-
pH	A	A	A	A	-	-	-	-	-	-

Key: A = 5 days/week; B = 1 or 2 days/week; - = analyses not performed

NOTE: Alkalinity, pH and volatile acid measurements were run on primary digester sludge, 1 or 2 days/week

DESCRIPTION OF EXPERIMENTAL PROGRAM AND PERFORMANCE RESULTS

The objectives of the plant-scale experimental work with alum were to determine the effectiveness of alum application in a final settling tank at a typical high-rate trickling filter plant as related to phosphorus removal and general enhancement of plant performance and to determine the sludge quantities resulting from the alum treatment.

During the first phase of the investigation, experiments were conducted at several alum dosage rates and with three different dosage program schedules. The objective during this phase was to determine which overall dosage rate and daily application schedule would be most effective. This phase extended from January 25 through May 25, 1972. During this entire period the flow was divided equally between the dosed and control trains.

The second phase of the program consisted of diverting lesser fractions of the total plant flow to the alum dosed train while maintaining an effective dosage program as determined in the first phase. The total amount of alum applied was, of course, reduced in proportion to flow. The objective of this phase was to determine the effect of hydraulic loading on final settling tank performance. This phase extended from June 3 through August 27, 1972.

During the final phase of the investigation, experiments were conducted using two polyelectrolytes along with alum to determine if polyelectrolyte addition would benefit the process. This phase extended from August 28 through October 5, 1972.

A summary of the experimental periods throughout the entire alum treatment investigation is given in Table 28. The alum dosage programs are shown in Table 29. Following are brief statements concerning the rationale for the 18 experimental periods into which the three general phases of the investigation were divided. Performance results for the 18 experimental periods for both the dosed and undosed trains are summarized in Tables 30 to 33.

Experimental Periods

Period 1. The Al(III) dosage was set at 93 kg/day (205 lb/day). Dosage Program A as shown in Table 28 was followed. Flow to the alum train averaged 5,413 m^3/day (1.43 mgd). The average alum $[Al_2(SO_4)_3 \cdot 14\ H_2O]$ concentration dosage was 195 mg/l. Based on influent or raw wastewater total phosphorus, Al:TP (mole) averaged 2.2. Effluent total phosphorus averaged 1.6 mg/l for the alum dosed train and 7.3 mg/l for the undosed train. Influent total phosphorus averaged 9.1 mg/l. Removals of BOD_5, TSS, and TOC were substantially higher on the train receiving alum treatment.

Period 2. The weight dosage of Al(III) was reduced to 90 percent of that of each time interval in Period 1. No change was made in the timing of the dosage program Flow to the alum train averaged 5,564 m^3/day (1.47 mgd). Alum concentration dosage averaged 171 mg/l, and the mean Al:influent TP (mole) was 1.8. Effluent total phosphorus for the alum train averaged 2.0 mg/l. As will be shown later, it is probable that the higher effluent total phosphorus was due to the slight increase in flow rate through the final settling tank.

TABLE 28

EXPERIMENTAL PERIODS FOR FULL-SCALE PHOSPHORUS REMOVAL STUDIES

Experimental Period No.	Dates	Dosage Program*	Percent Flow to Alum Train	Polyelectrolyte
1	1/25-2/13/72	A	50	-
2	2/15-2/25	B	50	-
3	2/26-3/8	C	50	-
4	3/9-3/19	D	50	-
5	3/20-3/26	E	50	-
6	3/27-4/6	A	50	-
7	4/7-4/20	F	50	-
8	4/26-5/25	F	50	-
9	6/3-6/19	G	33	-
10	6/24-7/11	H	20	-
11	7/17-8/2	I	40	-
12	8/21-8/27	F	50	-
13	8/28-8/30	F	50	Nalco 610 (0.1 mg/l)
14	9/6-9/11	F	50	-
15	9/12-9/17	F	50	Nalco 610 (0.1 mg/l)
16	9/18-9/21	J	50	Nalco 677 (1.0 mg/l)
17	9/25-9/28 9/30-10/3	J	50	Nalco 677 (0.3 mg/l)
18	10/4-10/5	G	50	Nalco 677 (0.3 mg/l)

*Refer to Table 29.

TABLE 29

ALUM DOSAGE PROGRAMS

Program	Time, hr	Al(III) Dosage Rate lb/day
A	0000-0300	181
	0300-0700	72
	0700-1000	181
	1000-2400	253
B	Same as A	A × 0.90
C	0000-0300	163
	0300-0700	0
	0700-1000	163
	1000-2400	228
D	Same as A	A × 0.85
E	Same as A	A × 0.80
F	2330-0300	181
	0300-0700	72
	0700-0930	181
	0930-2330	253
G	Same as F	F × 0.67
H	Same as F	F × 0.40
I	Same as F	F × 0.80
J	Same as F	F × 1.10

Conversion: 1 lb/day = 0.4536 kg/day

TABLE 30

MAIN PLANT PHOSPHORUS REMOVAL

Period No.	Dates	Inf. TP mg/l	Train No. 2 (Alum)						Train No. 1 (No Alum)				Remarks
			Flow mgd	Alum mg/l	Al:TP [mole]	Eff TP mg/l	Eff. Sol. P mg/l	% Rem'l TP	Flow mgd	Eff. TP mg/l	Eff. Sol. P mg/l	% Rem'l TP	
1	1/25/72-2/13/72	9.1	1.43	195	2.2	1.6(1)	0.9	82	1.43	9.1	3.8	0	(1) excludes eff. observation for 1/29/72: 6.7
2	2/15 -2/25	9.4	1.47	171	1.8	2.0	0.2	79	1.47	8.4	4.6	11	
3	2/28 -3/8	11.0	1.36	165	1.7	2.0(2)	0.2	82	1.36	8.8	5.9	20	(2) excludes eff. observation for 2/28/72: 6.9
4	3/9 -3/19	11.9	1.19	192	1.7	1.3	0.25	89	1.19	9.1	6.2	23	
5	3/20 -3/26	14.3	1.51	143	1.0	4.6	0.3	68	1.51	10.0	5.5	30	
6	3/27 -4/6	13.0	1.51	183	1.5	2.2(3)	0.2	83	1.51	10.5	6.6	19	(3) excludes eff. observation for 4/10/72: 11.7
7	4/7 -4/20	13.1	1.54	177	1.4	2.3	0.2	82	1.54	10.4	6.5	21	
8	4/26 -5/25	11.8	1.40	198	1.7	1.5	0.3	87	1.40	8.3	6.0	30	
9	6/3 -6/19	13.9	0.73	250	1.9	0.8	0.3	94	1.46	10.9	7.5	22	
10	6/24 -7/11	11.3	0.45	254	2.2	1.2	0.5	89	1.78	9.1	7.2	19	
11	7/17 -8/2	13.7	0.90	241	1.9	1.2	0.7	91	1.35	10.3	7.5	25	
12	8/21 -8/27	11.6	1.07	242	2.2	1.8	0.8	84	1.07	10.5	8.5	10	
13	8/28 -8/30	11.7	1.41	191	1.7	2.3	0.4	80	1.41	9.6	8.2	18	+ 0.1 mg/l Nalco 610 to Train No.2
14	9/6 -9/11	10.9	1.18	245	2.7	3.0	0.7	72	1.18	10.5	7.3	4	
15	9/12 -9/17	11.5	1.35	202	1.7	2.1	0.4	82	1.35	9.8	7.4	15	+ 0.1 mg/l Nalco 610 to Train No.2
16	9/18 -9/21	12.3	1.47	202	1.7	2.2	0.4	92	1.47	10.6	7.5	14	+ 1.0 mg/l Nalco 677 to Train No.2
17	9/25 -9/28 9/30 -10/3	14.1	1.42	212	1.6	2.6	0.5	82	1.42	----	---	--	+ 0.3 mg/l Nalco 677 to Train No.2
18	10/4 -10/5	12.2	1.62	113	0.95	4.4	1.0	64	1.62	9.7	7.7	21	+ 0.3 mg/l Nalco 677 to Train No.2

Conversion: 1 mgd = 3,785 m^3/day

TABLE 31

MAIN PLANT BOD$_5$ REMOVAL

			Train No. 2 (Alum)				Train No. 1 (No Alum)				
Period No.	Dates	Inf. BOD$_5$ mg/l	Flow mgd	Eff. BOD$_5$ mg/l	Eff. Sol. BOD$_5$ mg/l	% Rem'l BOD$_5$	Flow mg/l	Eff. BOD$_5$ mg/l	Eff. Sol. BOD$_5$ mg/l	% Rem'l BOD$_5$	Remarks
1	1/25/72-2/13/72	174	1.43	19(4)	-	89	1.43	39	-	76	(4) excludes eff. observation for 1/25/72: 63
2	2/15 -2/25	153	1.47	16	-	90	1.47	52	-	66	
3	2/26 -3/8	159	1.36	16	-	90	1.36	44	-	72	
4	3/9 -3/19	169	1.19	13	-	92	1.19	43	-	74	
5	3/20 -3/26	149	1.51	17	-	89	1.51	47	-	70	
6	3/27 -4/6	173	1.51	14	-	92	1.51	41	-	76	
7	4/7 -4/20	190	1.54	15	-	92	1.54	52	-	72	
8	4/26 -5/25	160	1.40	11	5	93	1.40	35	8	78	
9	6/3 -6/19	223	0.73	9	3	96	1.46	51	14	77	
10	6/24 -7/11	173	0.45	9	5	95	1.78	36	16	79	
11	7/17 -8/2	223	0.90	11	5	95	1.35	52	13	76	
12	8/21 -8/27	176	1.07	17	5	91	1.07	35	9	81	
13	8/28 -8/30	178	1.41	19	9	89	1.41	24	12	86	
14	9/6 -9/11	164	1.18	14	6	91	1.18	27	13	83	+ 0.1 mg/l Nalco 610 to Train No. 2
15	9/12 -9/17	160	1.35	17	7	89	1.35	33	11	79	
16	9/18 -9/21	176	1.47	17	9	90	1.47	50	11	.73	+ 0.1 mg/l Nalco 610 to Train No. 2 + 1.0 mg/l Nalco 677 to Train No. 2
17	{9/25 -9/28 9/30 -10/3	177	1.42	21	11	88	1.42	41	17	77	+ 0.3 mg/l Nalco 677 to Train No. 2
18	10/4 -10/5	196	1.62	18	12	91	1.62	28	14	86	+ 0.3 mg/l Nalco 677 to Train No. 2

Conversion: 1 mgd = 3,785 m^3/day

TABLE 32

MAIN PLANT TOTAL SUSPENDED SOLIDS REMOVAL

Period No.	Dates	Inf. TSS mg/l	Train No. 1 (Alum) Flow mgd	Train No. 1 (Alum) Eff. TSS mg/l	Train No. 1 (Alum) % Rem'l TSS	Train No. 2 (No Alum) Flow mgd	Train No. 2 (No Alum) Eff. TSS mg/l	Train No. 2 (No Alum) % Rem'l TSS	Remarks
1	1/25/72-2/13/72	167	1.43	29	83	1.43	63	63	
2	2/15 -2/25	175	1.47	29	82	1.47	57	65	
3	2/26 -3/8	200	1.36	30	84	1.36	55	71	
4	3/9 -3/19	227	1.19	27	87	1.19	58	74	
5	3/20 -3/26	258	1.51	45	81	1.51	69	69	
6	3/27 -4/6	245	1.51	38	83	1.51	77	67	
7	4/7 -4/20	319	1.54	49	84	1.54	74	76	
8	4/26 -5/25	267	1.40	25	90	1.40	56	78	
9	6/3 -6/19	310	0.73	20	96	1.46	72	77	
10	6/24 -7/11	229	0.45	19	92	1.78	43	81	
11	7/17 -8/2	291	0.90	15	94	1.35	56	81	
12	8/21 -8/27	240	1.07	22	90	1.07	43	82	
13	8/28 -8/30	323	1.41	30	90	1.41	37	88	+ 0.1 mg/l Nalco 610 to Train No. 2
14	9/6 -9/11	230	1.18	28	88	1.18	38	84	
15	9/12 -9/17	253	1.35	24	90	1.35	51	79	+ 0.1 mg/l Nalco 610 to Train No. 2
16	9/18 -9/21	230	1.47	25	89	1.47	51	78	+ 1.0 mg/l Nalco 677 to Train No. 2
17	9/25 -9/28 9/30 -10/3	268	1.42	23	91	1.42	53	80	+ 0.3 mg/l Nalco 677 to Train No. 2
18	10/4 -10/5	261	1.62	32	88	1.62	33	87	+ 0.3 mg/l Nalco 677 to Train No. 2

Conversion: 1 mgd = 3,785 m^3/day

TABLE 33

MAIN PLANT TOTAL ORGANIC CARBON REMOVAL

			Train No. 2 (Alum)				Train No. 1 (No Alum)				
Period No.	Date	Inf. TOC mg/l	Flow mgd	Eff. TOC mg/l	Eff. Sol. TOC mg/l	$ Rem'l TOC	Flow mgd	Eff. TOC mg/l	Eff. Sol. TOC mg/l	$ Rem'l TOC	Remarks
1	1/25/72-2/13/72	151	1.43	22	15	84	1.43	59	38	58	
2	2/15 -2/25	147	1.47	28	20	81	1.47	51	36	65	
3	2/26 -3/8	154	1.36	25	17	82	1.36	56	22	62	
4	3/9 -3/19	182	1.19	22	20	88	1.19	61	31	66	
5	3/20 -3/26	220	1.51	36	25	84	1.51	77	36	65	
6	3/27 -4/6	195	1.51	37	26	79	1.51	78	44	58	
7	4/7 -4/20	250	1.54	32	21	87	1.54	82	37	67	
8	4/26 -5/25	162	1.40	17	12	89	1.40	44	19	72	
9	6/3 -6/19	193	0.73	15	15	92	1.46	44	31	62	
10	6/24 -7/11	151	0.45	12	9	92	1.78	42	21	72	
11	7/17 -8/2	198	0.90	13	12	93	1.35	55	23	73	
12	8/21 -8/27	193	1.07	19	15	90	1.07	45	29	76	
13	8/28 -8/30	166	1.41	19	12	89	1.41	38	24	77	+ 0.1 mg/l Nalco 610 to Train No. 2
14	9/6 -9/11	174	1.18	21	14	88	1.18	41	23	76	
15	9/12 -9/17	100	1.35	23	16	87	1.35	42	22	76	+ 0.1 mg/l Nalco 610 to Train No. 2
16	9/18 -9/21	182	1.47	23	13	87	1.47	48	22	73	+ 1.0 mg/l Nalco 677 to Train No. 2
17	9/25 -9/28 9/30 -10/3	192	1.42	22	13	88	1.42	52	22	73	+ 0.3 mg/l Nalco 677 to Train No. 2
18	10/4 -10/5	149	1.62	20	12	86	1.62	29	22	80	+ 0.3 mg/l Nalco 677 to Train No. 2

Conversion: 1 mgd = 3,785 m^3/day

Period 3. The weight rates of Al(III) application for the different time intervals were maintained the same as in Period 2 with the exception of the low flow interval from 0300 to 0700 hr. During this interval, both alum feed pumps were shut off. It was hypothesized that elimination of alum dosage during the hours of low flow would make little difference in terms of daily phosphorus removal or overall plant performance. The data in Tables 30 to 33 indicate this hypothesis was correct. However, during the early morning hours, a rather high degree of turbidity was noted in the final settling tank. This dosage method was, therefore, discontinued. Alum concentration dosage and Al:influent TP (mole) during this period averaged 165 mg/l and 1.7, respectively. Flow to the alum train averaged 5,148 m^3/day (1.36 mgd). This lower flow may account for relatively small changes in plant efficiency at the decreased alum dosage.

Period 4. The weight dosage of Al(III) applied was maintained at 85 percent of that applied in each time interval during Period 1. Dosage between 0300 and 0700 hr was resumed. Flow entering the alum train during this period was less than usual, 4,504 m^3/day (1.19 mgd), because of University holidays. Alum concentration dosage averaged 192 mg/l and the mean Al:influent TP (mole) was 1.7. Average removals of phosphorus, BOD_5, TSS, and TOC were higher than in any of the previous periods. This increase in efficiency can probably be attributed to improved flocculation and solids capture in the final clarifier at the reduced flow.

Period 5. During Period 5, the Al(III) weight dosage during each time interval was reduced to 80 percent of that applied in Period 1. The flow to the alum train during this period averaged 1.51 mgd, the highest to this point in the experimental program. The high flow and a higher influent total phosphorus concentration, along with the reduced alum dosage, resulted in a mean Al: influent TP (mole) of 1.0. Removals of phosphorus, TSS, and TOC were reduced, particularly phosphorus. It is interesting to note, however, that the soluble phosphorus in the effluent was about the same as in earlier periods. This seems to indicate that phosphorus was precipitated but that too little Al(III) remained for coagulation and formation of good settleable floc. A well-formed floc is obviously necessary to entrain the precipitated aluminum phosphate and other nonsettleable solids if the process is to function effectively.

Period 6. On the basis of the results of the first five periods, the Al(III) dosage pattern was set the same as during the first period, 93 kg/day (205 lb/day). The dosage program was also maintained on the same time schedule as in Period 1. Effluent phosphorus during this period averaged 2.2 mg/l, as compared with 1.6 mg/l during the first period. On the other hand, the alum train average influent was 5,715 m^3/day (1.51 mgd) as compared with 5,413 m^3/day (1.43 mgd) during the first period. Although the mean Al:influent TP (mole) was 1.5, it seems probable, as will be shown later, that the reduced removal of phosphorus was primarily a result of the high flow through the final settling tank.

Period 7. During earlier periods, a higher than normal turbidity was observed in the final effluent from 0900 to 1000 hr. It was thought that this was due to insufficient alum dosage, relative to flow and phosphorus loading, as is apparent in Figure 18. Therefore, the time when the highest alum dosage was applied was advanced 30 minutes, i.e., the high and low pumps were operated from 0930 to 2330 hr. The total daily Al(III) dosage was maintained at 93 kg/day (205 lb/day).

Period 8. During all earlier periods when the alum treatment process was functioning efficiently, well-formed floc particles were observed escaping over the effluent weirs of the final settling tank. It was thought that floc capture might be improved if the escaping floc were entrained in a sludge blanket in the settling tank. It was hypothesized that a deeper annular skirt in the center of the settling tank might enhance the formation of a sludge blanket and help prevent short circuiting. Accordingly, during the period from April 21 to April 24, 1972, the skirt was extended from 72 cm (30 in) to 198 cm (78 in) below the settling tank water surface. After installation of the skirt extension, the Al(III) weight dosage program was continued as in Period 7. The mean Al:influent TP (mole) during this period was 1.7, and alum train influent flow was 5,299 m^3/day (1.40 mgd). Effluent phosphorus averaged 1.5 mg/l and removals of BOD_5, TSS, and TOC were higher than during any previous period. It is difficult to prove that the skirt extension enhanced the process, but it certainly did no harm.

Period 9. Beginning with this period and continuing through Period 11, lesser fractions than 50 percent of the influent flow were diverted to the plant train receiving alum treatment. The objective was to investigate the effect of final settling tank hydraulic loading on process performance. Al(III) weight dosages were maintained at 67 percent of those utilized for the four time intervals in Periods 7 and 8. During Period 9, 33 percent of the total plant influent flow was directed to the alum dosed train. The daily dosage of Al(III) was 62 kg (137 lb). The average flow to the alum train was 2,763 m^3/day (0.73 mgd). The Al:influent TP (mole) averaged 1.9, and alum concentration dosage was 250 mg/l. The alum dosage was high as the flow was lower than anticipated. Effluent phosphorus averaged 0.8 mg/l and removals of BOD_5 and TSS were the highest experienced in the entire program. One might speculate that the excellent removal was a result of a high alum dosage. Later analysis indicates that final tank hydraulic loading was the most significant factor.

Period 10. During this period, only 20 percent, 1,703 m^3/day (0.45 mgd), of the total plant flow was directed to the alum treatment train, the lowest experienced during the entire program. The Al(III) weight dosage was accordingly reduced to 40 percent of that applied during Periods 7 and 8, maintaining the same dosage time schedule. Effluent BOD_5, TSS, and TOC were similar to those in Period 9. Total phosphorus concentration in the effluent was higher than expected (1.2 mg/l). Examination of the individual daily data does not reveal any factor to account for this apparent anomaly.

Period 11. Forty (40) percent of plant flow was directed to the alum train during this period, and the Al(III) weight dosage schedule was held at 80 percent of the rates used in Periods 7 and 8. Alum train influent flow averaged 3,407 m^3/day (0.90 mgd). The mean Al:influent TP (mole) was 1.9, and the alum concentration dosage was 241 mg/l. Excellent removals of BOD_5, TSS, and TOC were obtained. Before assuming that the high alum dosage accounted for the high removals, the results during Period 4 should be reviewed. Effluent phosphorus averaged 1.3 mg/l during Period 4 even though the alum concentration dosage was less than 200 mg/l. The influent flow during Period 4 was only 4,504 m^3/day (1.19 mgd).

Period 12. During this period, the division of flow between the two trains of the plant was equal. Flow averaged 4,050 m^3/day (1.07 mgd) to each train. Al (III) dosage was maintained at 93 kg/day (205 lb/day). Effluent total phosphorus averaged 1.8 mg/l, higher than expected based on earlier results.

Period 13. Flow division was continued at 50 percent to each train. The dosage of Al(III) was continued at 93 kg/day (205 lb/day), and the application of Nalco 610 was initiated. Nalco 610 is a high molecular weight cationic polyelectrolyte designed for use in sludge dewatering and wastewater clarification.

The polyelectrolyte was applied with two small positive displacement feed pumps programmed to operate from the same timing system as the alum pumps. Polyelectrolyte dosage was maintained at an average of 0.1 mg/l, selected on the basis of laboratory jar tests. The test run during this period was quite short (3 days) and, although no improvement in effluent quality was apparent, the results should not be considered conclusive.

Period 14. Difficulties with the preparation of polyelectrolyte solution resulted in the temporary cessation of polyelectrolyte addition. While awaiting the delivery of polyelectrolyte dispersion equipment, the dosage of Al(III) was continued at 93 kg/day (205 lb/day). Phosphorus removal during this period was disappointing.

Period 15. The addition of Nalco 610 polyelectrolyte was resumed during this period. Al(III) dosage was maintained at 93 kg/day (205 lb/day). Polyelectrolyte addition was again set at 0.1 mg/l. No significant improvement in performance was observed.

Period 16. During this period, Nalco 677 was added at the rate of 1.0 mg/l. Nalco 677 is a liquid anionic polyelectrolyte designed to enhance the removal of suspended solids in municipal or industrial wastewater treatment applications. The dosage of Al(III) was increased to 102 kg/day (225 lb/day), or 10 percent more than the daily rate employed in Periods 12 through 15. No significant improvement in performance was noted.

Period 17. Dosage of Nalco 677 was continued but was reduced to 0.3 mg/l following consultation with a company representative. Al(III) dosage was maintained at 102 kg/day (225 lb/day). Some difficulties were experienced with lumps of undissolved polyelectrolyte clogging the feed pumps. In addition, it was found that one check valve on an alum feed pump was sticking. Performance results during this period were disappointing.

Period 18. Al(III) dosage was reduced to 67 percent, 62 kg/day (137 lb/day), of that used in Periods 12 through 15, while Nalco 677 continued to be fed at 0.1 mg/l. It was hoped that the polyelectrolyte would improve the settling characteristics of the floc to the extent that substantially lower alum dosages would be effective. Unfortunately, this test coincided with a period of high plant flow. The resulting Al:influent TP (mole) ratio was less than 1.0 and phosphorus removal was seriously reduced.

DISCUSSION OF RESULTS

The overall improvement in performance of the alum dosed train versus the undosed train is obvious in Tables 30 to 33. Total phosphorus removal averaged 82 percent on the alum train and 18 percent on the undosed train during the entire set of experimental periods. Other average treatment efficiencies were as follows: BOD_5 removal, 91 percent versus 77 percent; total suspended solids removal, 88 percent versus 77 percent; total organic carbon removal, 87 percent versus 69 percent.

Examination of average results indicates that the single most important variable affecting the removal of phosphorus, BOD_5, TSS, and TOC on the alum treatment train was flow rate. This effect was visually evident during the entire experimental program, i.e., when the flow through the final settling tank was less than 4,542 m^3/day (1.2 mgd), the tank effluent was quite clear and only a few small floc particles could be observed passing over the effluent weir. At higher flow rates, larger floc particles could be seen and the effluent turbidity was higher. The alum treatment process used at Chapel Hill functioned well at alum dosages between 175 and 250 mg/l and an Al:influent TP (mole) between 1.4 and 2.2. Within these ranges, the final tank hydraulic loading appears to be the principal factor controlling process efficiency.

It is also apparent that when the Al:influent TP (mole) approaches 1.0, phosphorus is precipitated but not effectively settled, as illustrated by the results during Period 5. During this period, effluent total phosphorus averaged 4.5 mg/l, the highest during the experimental program; however, effluent soluble phosphorus averaged only 0.3 mg/l.

The effect of final settling tank hydraulic loading or surface overflow rate on process efficiency can be seen in Figures 20 to 22. The data plotted on these graphs do not include the results of Period 5 when the Al:influent TP (mole) was 1.0, nor those of Periods 13 through 19 during which polyelectrolytes were used in addition to alum. Plots of Al:influent TP (mole) versus mean removals for the experimental period yielded no apparent trend. An upward trend in removal of phosphorus and other constituents was noted with increasing alum dosage, but this can largely be explained by the fact that at any particular alum weight feed rate, the alum concentration was inversely proportional to flow. It is interesting to note that when the flow to the final settling tank in which alum was being applied was less than 50 percent of plant flow (Periods 9, 10, and 11), the percentage removal of total phosphorus, BOD_5, total organic carbon, and total suspended solids averaged higher than during any other period.

It is also significant that the levels of soluble phosphorus, soluble BOD_5, and soluble organic carbon were substantially lower than the total values during all experimental periods. The amount of these soluble constituents remaining after treatment gives an indication of the effluent quality which might be obtained with the use of effective fine solids removal facilities following secondary clarification.

As mentioned earlier, settled sludge from the final clarifiers was returned to the primary clarifiers where it resettled along with raw wastewater solids. The return of alum sludge had a significant effect on the performance of the

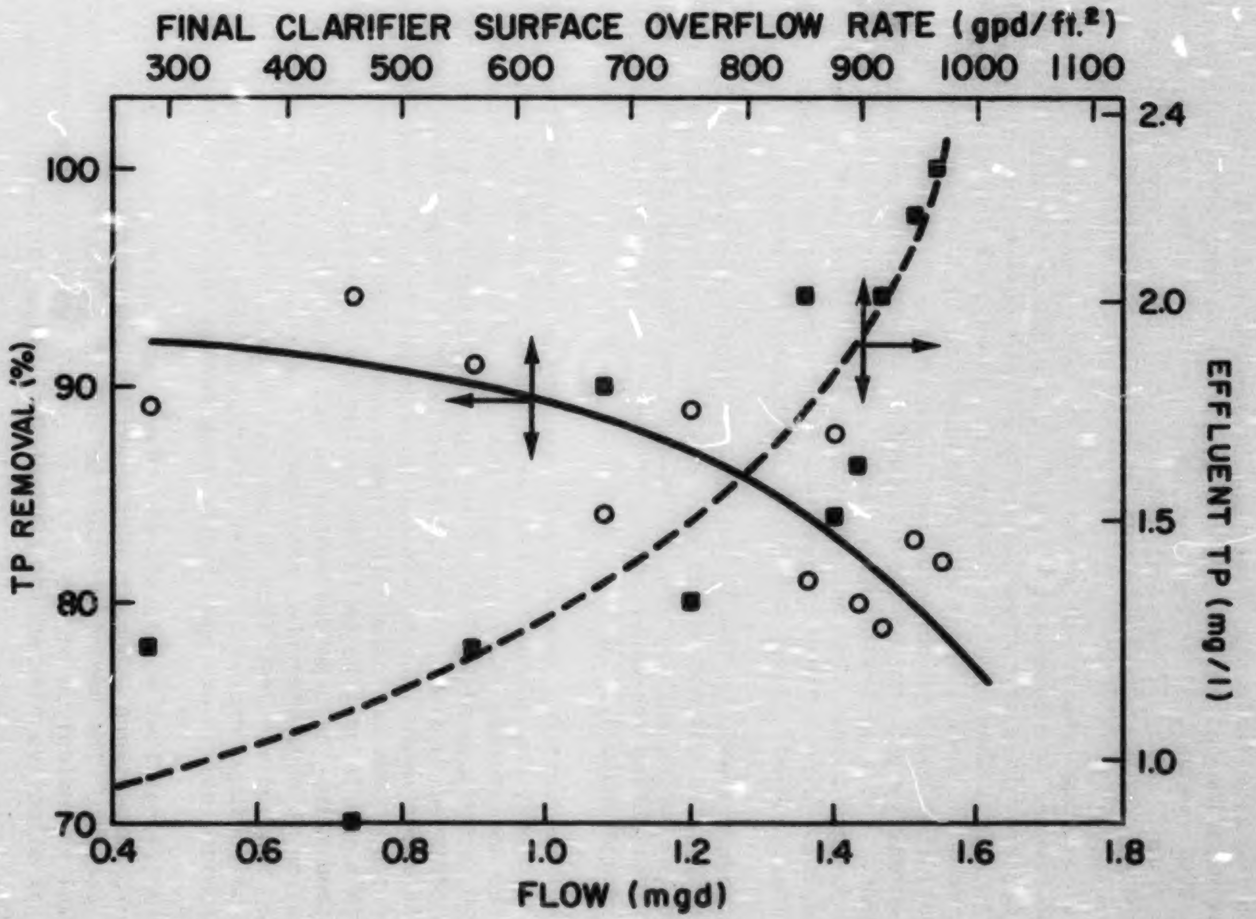


FIGURE 20. TOTAL PHOSPHORUS REMOVAL AS A FUNCTION OF FLOW AND FINAL CLARIFIER OVERFLOW RATE FOR EXPERIMENTAL PERIODS 1 THROUGH 4 AND 6 THROUGH 12.

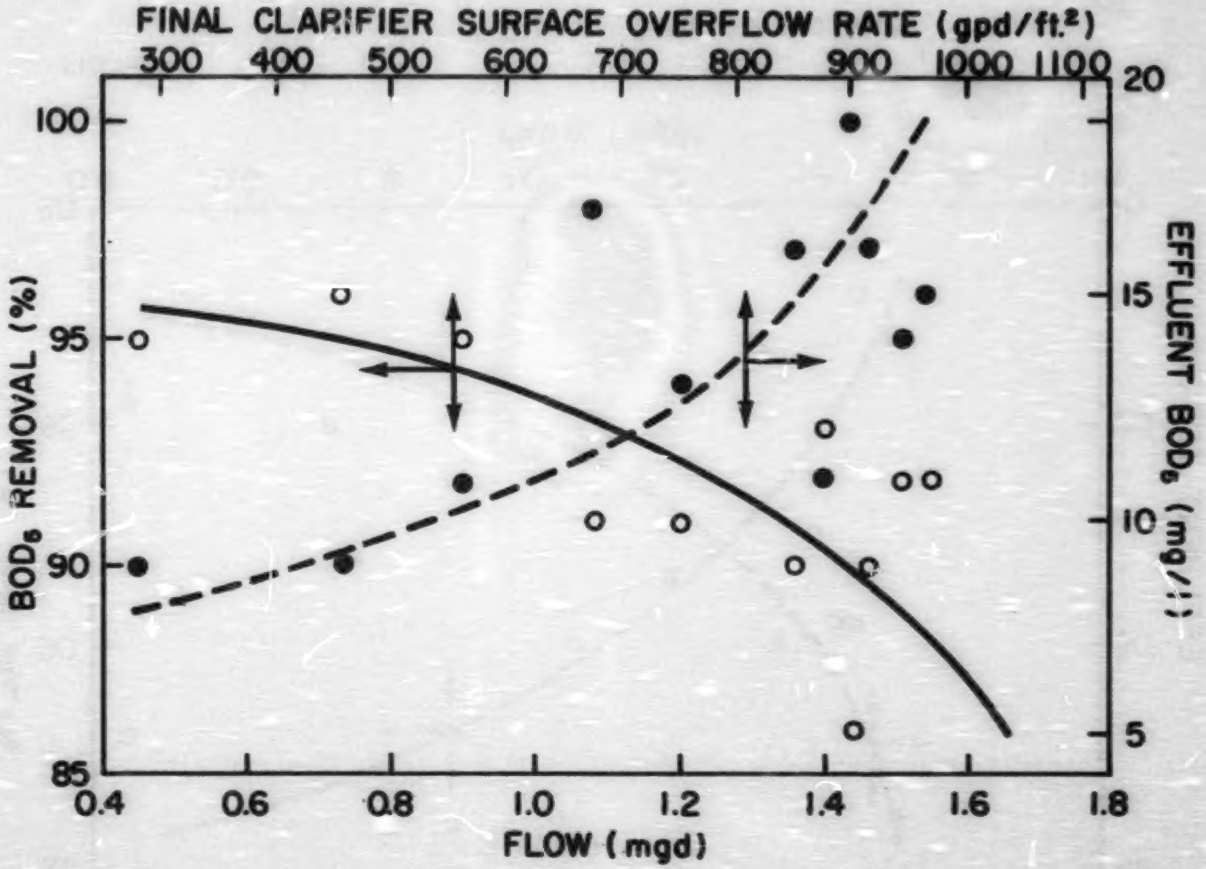


FIGURE 21. BOD$_5$ REMOVAL AS A FUNCTION OF FLOW AND FINAL CLARIFIER OVERFLOW RATE FOR EXPERIMENTAL PERIODS 1 THROUGH 4 AND 6 THROUGH 12.

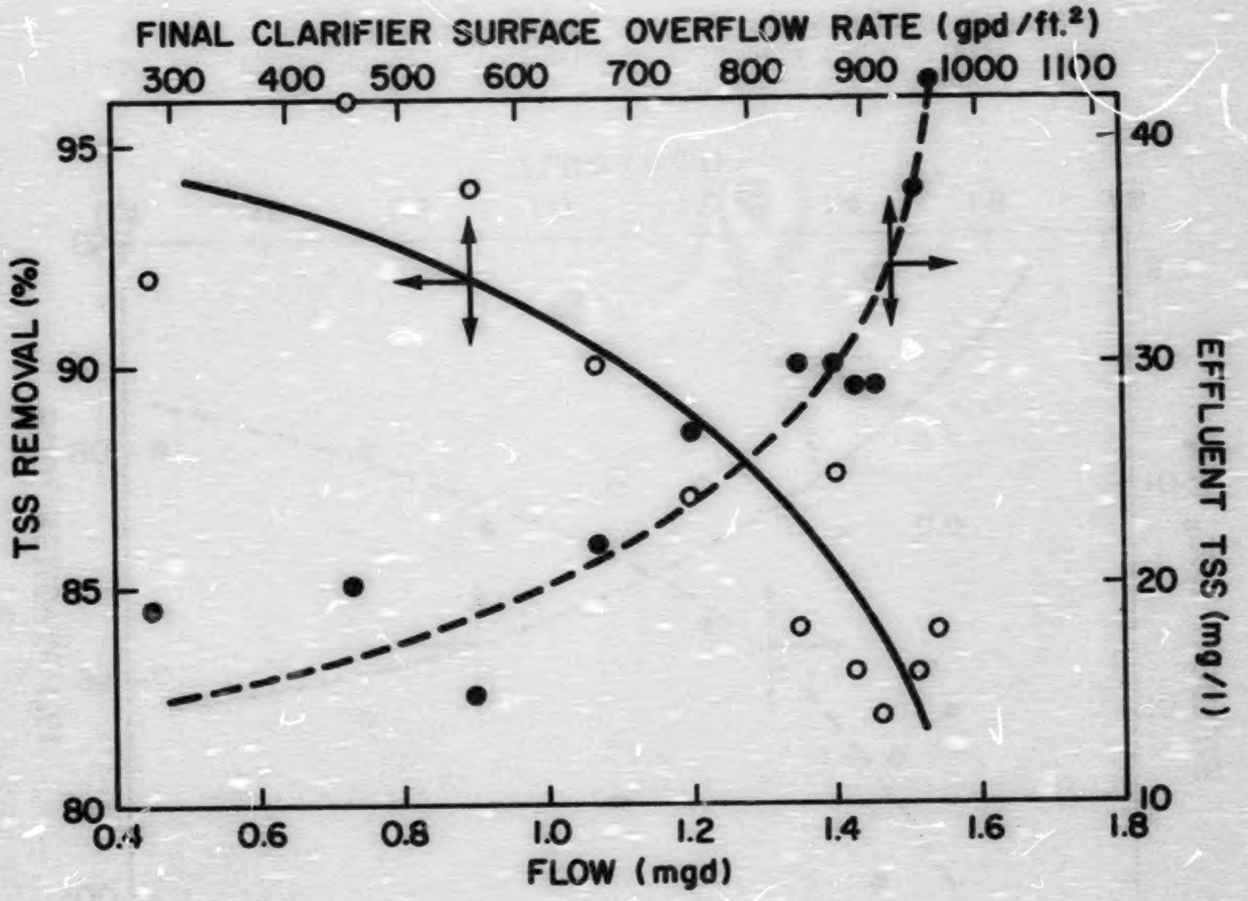


FIGURE 22. TOTAL SUSPENDED SOLIDS REMOVAL AS A FUNCTION OF FLOW AND FINAL CLARIFIER OVERFLOW RATE FOR EXPERIMENTAL PERIODS 1 THROUGH 4 AND 6 THROUGH 12.

primary clarifier to which it was returned. Table 34 summarizes primary effluent characteristics on the plant trains during the period from 1/27/72 to 8/30/72.

TABLE 34

QUALITY OF PRIMARY EFFLUENT FROM 1/27/72 to 8/30/72

	Train No. 1 (Alum)			Train No. 2 (No Alum)		
Exp. Period	BOD_5 mg/l	TSS mg/l	TP mg/l	BOD_5 mg/l	TSS mg/l	TP mg/l
1	64	59	5.3	76	71	8.3
2	73	72	7.1	82	80	8.5
3	65	59	6.9	78	71	9.3
4	59	53	5.8	82	84	10.3
5	63	70	7.5	70	95	11.0
6	63	88	8.4	78	123	11.5
7	65	77	7.0	81	103	10.7
8	50	93	6.1	64	65	9.1
9	58	76	5.3	93	49	10.9
10	30	27	4.7	64	60	9.1
11	51	43	5.4	93	79	10.8
12	52	50	6.8	80	64	10.4
13	45	62	7.9	65	92	9.9

As Table 34 indicates, the removal of BOD_5 and total suspended solids was significantly higher in the primary clarifier to which the alum sludge was returned. The reduction in influent total phosphorus was even greater. Influent total phosphorus was reduced from an average concentration of 11.6 mg/l to 10.0 mg/l, or 14 percent, in the primary clarifier which received no alum sludge. The primary clarifier receiving return alum sludge reduced the influent total phosphorus to an average concentration of 6.5 mg/l (a 44 percent reduction). Obviously the return of alum sludge enhanced primary clarifier settling efficiency. The improved phosphorus removal was probably due to a combination of enhanced settling efficiency and adsorption of phosphorus on the floc structure.

Although it was possible to control the fraction of plant influent entering either side of the plant, the actual amount of flow entering either train on any particular day or at any particular time could not be controlled. Both flow and influent phosphorus concentration varied from day to day. No means were available, however, to automatically vary alum feed rate with flow or influent phosphorus concentration. Consequently, the daily dosage of alum in mg/l and the daily Al:influent TP (mole) varied during any given experimental period. Because of these variations, a number of statistical procedures were used treating each day's data as a separate experiment in an attempt to develop some meaningful correlations.

Data Sorting Procedures

A computerized data sorting method was the first technique used in analyses of daily data. Because flow appeared to be the most important single factor affecting performance, flow was included in each sorting. Five flow intervals were used:

1,438-2,971 m^3/day	(0.38-0.78 mgd)
2,972-4,334 m^3/day	(0.79-1.14 mgd)
4,335-5,129 m^3/day	(1.15-1.35 mgd)
5,130-5,886 m^3/day	(1.36-1.55 mgd)
5,887-7,002 m^3/day	(1.56-1.85 mgd)

In the first sorting, the data were separated into three levels of total phosphorus removal: 70-78 percent, 79-87 percent, and 88-96 percent. The printout listed alum dosage in mg/l, Al:influent TP (mole), influent total phosphorus concentration, total suspended solids in final settling tank influent, flow, percent removal of total suspended solids, and percent removal of total phosphorus.

The pertinent questions and observations derived from the first sorting follow:

Q: Is the percent removal of total phosphorus or total suspended solids influenced by flow?

A: Yes, removal decreased as flow increased.

Q: Is the percent removal of total phosphorus or total suspended solids influenced by alum concentration dosage or Al:influent TP (mole)?

A: Increased flow resulted in decreased alum concentration dosage and Al:influent TP (mole). The data did, however, include some days when the alum concentration dosage and Al:influent TP (mole) were high even though the flow was high. On such days, relatively poor removals were obtained, indicating that the important variable was flow rather than alum concentration dosage or Al:influent TP (mole).

Q: Does the concentration of total suspended solids in the influent to the final settling tank (trickling filter effluent) have an effect on removal of total phosphorus or total suspended solids? (The basis for this question is that a high concentration of colloidal matter in settling tank influent may require more alum for destabilization, thereby affecting precipitation of phosphorus or removal of suspended solids).

A: The amount of total suspended solids in final settling tank influent seemed to have little effect on the removal of either total suspended solids or total phosphorus.

In the second sorting, data were separated into the previously listed flow ranges and also into four alum concentration dosage categories: 130-165 mg/l, 166-210 mg/l, 211-260 mg/l, and 261-310 mg/l. The printout listed the same variables as the first sorting. The pertinent question and observation derived from the second sorting is as follows:

Q: Considering the two variables flow and alum concentration dosage, which one produces the most significant effect on removal of total phosphorus and total suspended solids?

A: Decreased flows and increased alum concentration dosages appeared to result in increased removal of total phosphorus. In general, as flow increased, alum concentration dosage decreased. On the basis of this sorting, it was impossible to determine the separate effects of alum concentration dosage and flow.

The third sorting listed data by flow categories and also by Al:influent TP (mole) ranges as follow: 1.2-1.7, 1.8-2.4, and 2.5-3.1. The pertinent question and observation emanating from the third sorting are given below:

Q: Is the removal of total phosphorus and total suspended solids affected more by flow or by Al:influent TP (mole)?

A: Increasing the Al:influent TP (mole) above 1.4 results in little if any observable improvement in total phosphorus and total suspended solids removal.

The fourth sorting simply listed flow categories along with percent total phosphorus removal and the pH of the final effluent. The pertinent questions and observations were as follows:

Q: Is there a relationship between flow and total phosphorus removal?

A: Yes, as shown in Figure 23.

Q: Is pH affected by flow?

A: Yes, low flows are normally coincident with high alum concentration dosages and consequently with low pH values.

Scattergrams of the data used in the sorting analysis are shown in Figures 24 to 26. The general trend of increasing total phosphorus removal with increasing alum concentration dosage and decreasing flow is apparent. The lack of any trend in total phosphorus removal with the Al:influent TP (mole) can also be seen. Because the amount of alum fed each day during any experimental period was fixed, the alum concentration depended on flow, decreasing as flow increased. Statistically, therefore, it is difficult to independently determine the effect of flow and alum concentration dosage.

A plot of percent total phosphorus removal versus alum concentration dosage is shown in Figure 27. The odd point on this chart is the average of phosphorus removals and alum concentration dosage on 11 days when both flow and alum concentration were high: flow > 5,299 m^3/day (1.40 mgd) and alum dosage > 190 mg/l. This point does not correspond with the curve in Figure 27. It does, however, correspond well with the curve in Figure 23. This indicates that above some minimum alum concentration dosage, flow is the more significant factor affecting total phosphorus removal. If sufficient project funds had been available to install an alum feeding system automatically paced by plant flow, the alum feed concentration could have been maintained at any desired level and more definitive results might have been obtained relative to the effect of this variable.

Regression Analysis

Attempts were made to fit various types of regression equations to the daily plant data. In one set, the dependent variable was percent total phosphorus remaining in the plant effluent. Independent variables were various combinations of flow, alum concentration dosage, Al:influent TP (mole), influent total phosphorus concentration, and trickling filter effluent total phosphorus concentration. In another set, the dependent variable was plant effluent total phosphorus concentration. Both linear and log-linear equations were fitted to the data, but in all cases, the multiple R^2 value was less than 0.35. Because of the very low correlations obtained, the various regression equations are not reported here. It is believed the performance data for the 18 experimental periods are summarized in Tables 30 to 33, along with the general results of the sorting analyses, present the best view of the alum treatment process as operated at Chapel Hill.

Sludge Production

The incremental sludge production which results from the addition of alum or any other coagulant to a wastewater treatment plant is an essential item of data to both the designer and the plant operator. The effect of the combined organic-

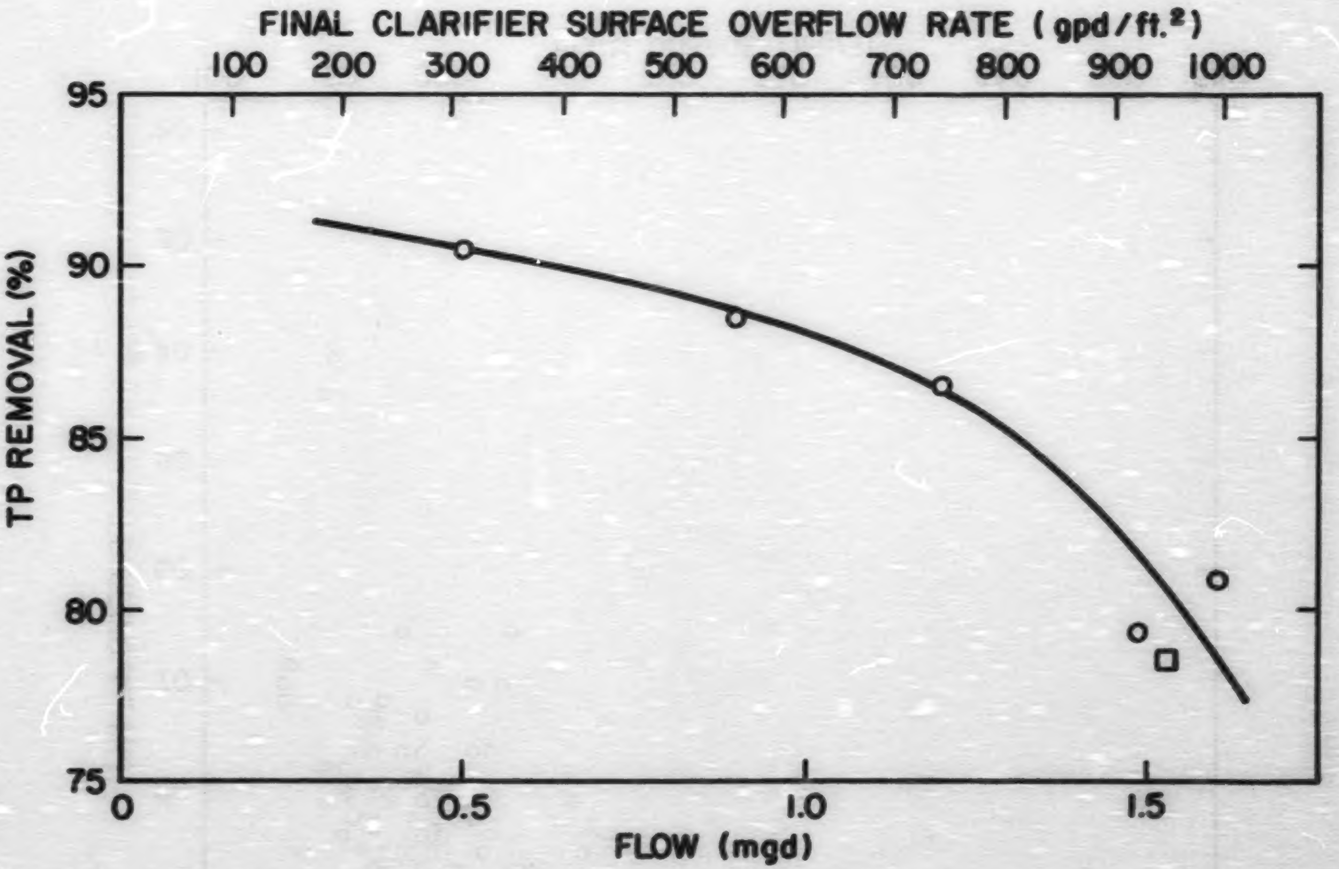


FIGURE 23. EFFECT OF FLOW ON TOTAL PHOSPHORUS REMOVAL FROM SORTING ANALYSIS.

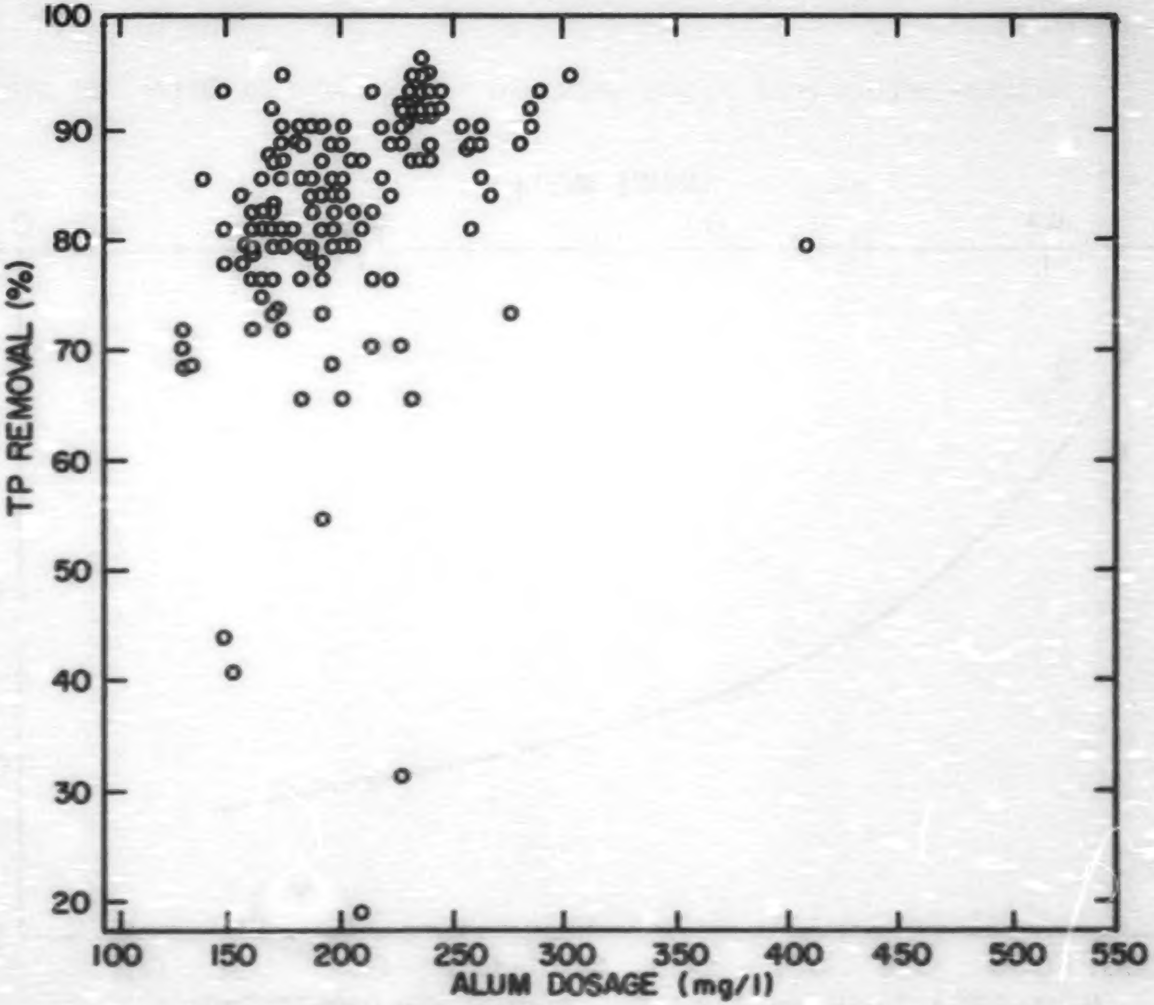


FIGURE 24. SCATTERGRAM FOR ALUM CONCENTRATION DOSAGE VERSUS PERCENT TOTAL PHOSPHORUS REMOVAL.

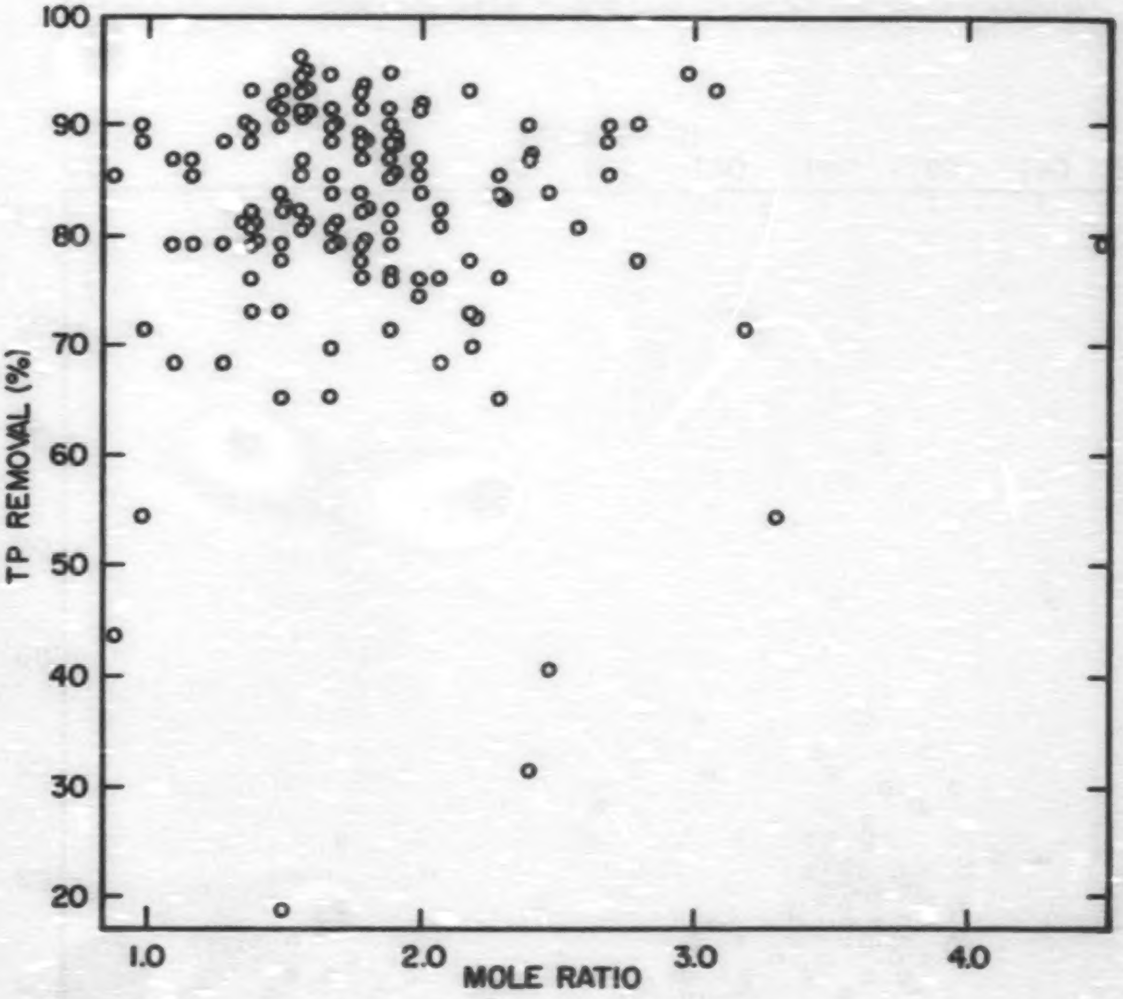


FIGURE 25. SCATTERGRAM FOR AL:INFLUENT TP (MOLE) VERSUS PERCENT TOTAL PHOSPHORUS REMOVAL.

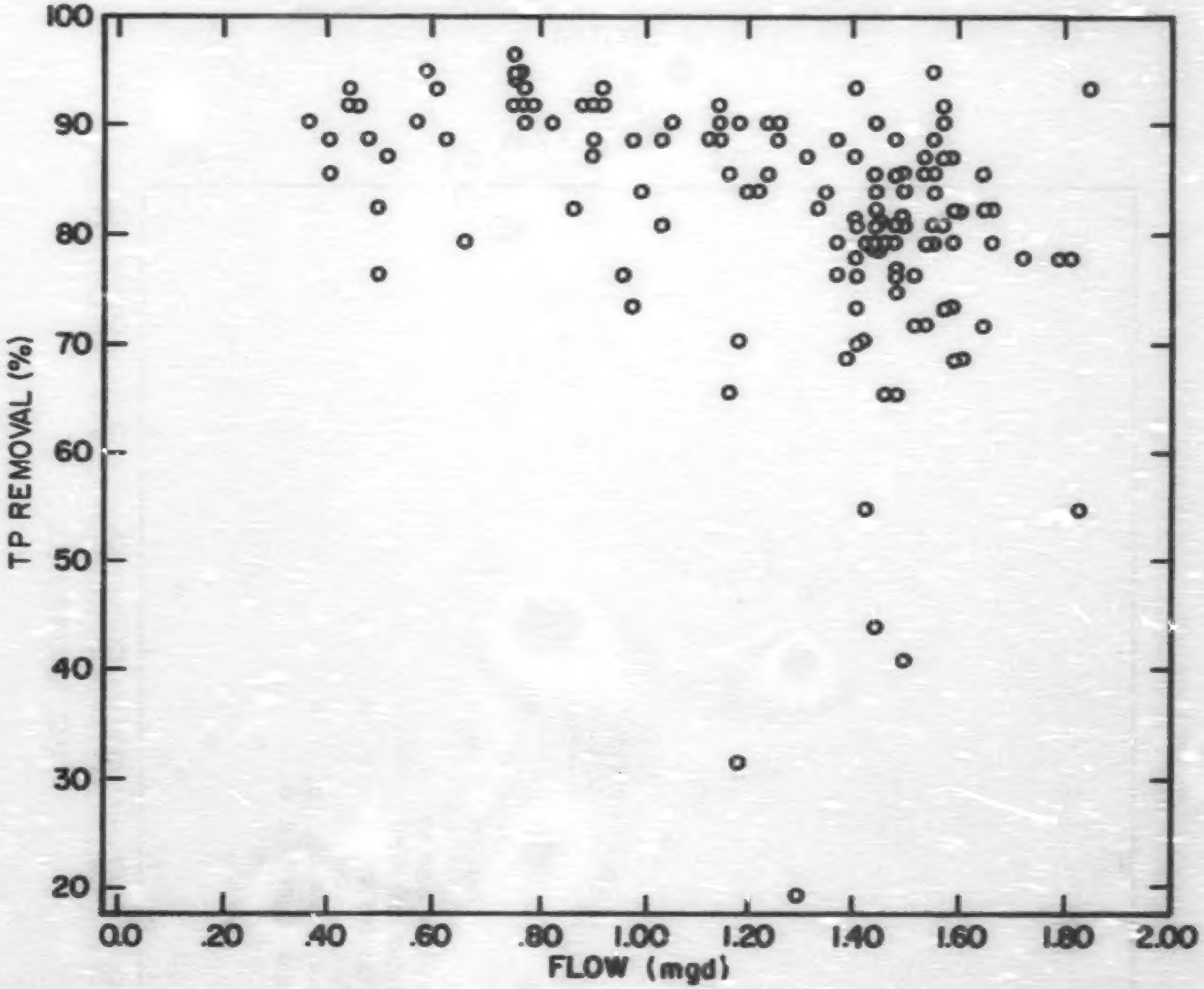


FIGURE 26. SCATTERGRAM FOR FLOW VERSUS PERCENT TOTAL PHOSPHORUS REMOVAL.

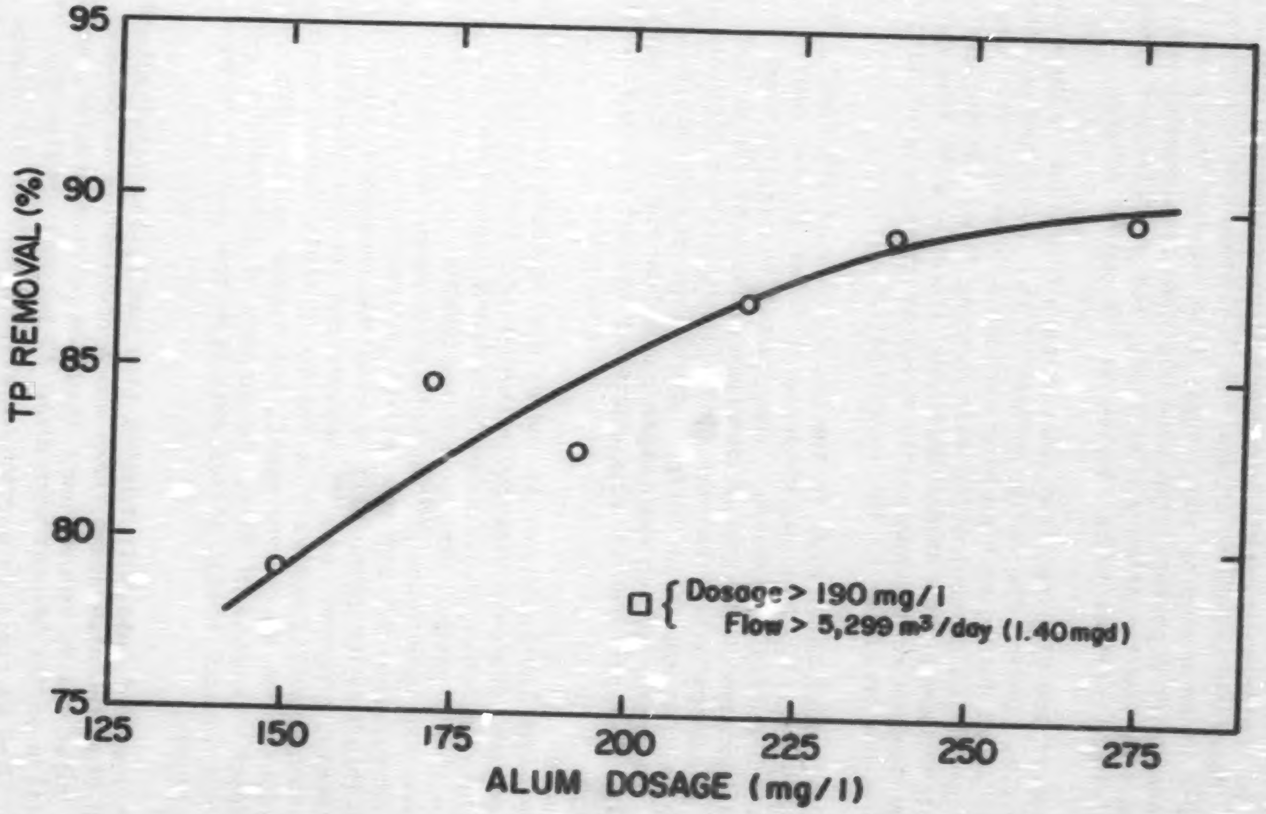


FIGURE 27. EFFECT OF ALUM CONCENTRATION DOSAGE ON TOTAL PHOSPHORUS REMOVAL FROM SORTING ANALYSIS.

chemical sludges on solids treatment and disposal systems is another important consideration.

At the Chapel Hill Plant, the secondary sludge settling in the final clarifiers is returned to the primary clarifiers where it resettles and combines with the raw sludge. Separate secondary sludge return systems are used on each train, i.e., there is no mixing of the sludges from the two trains until they combine in the anaerobic digester. The same positive displacement pump is used to remove sludge from the two primary clarifiers, but at different times permitting the individual sludges to be sampled at the pump discharge.

Sludge was pumped to the digester from each primary clarifier twice a day, at 7 a.m. and 5 p.m. During the early periods of the investigation, three samples were collected during each pumping period to determine the rate of decrease in sludge solids concentration with pumping time. On the average, the solids concentration of the sludge decreased linearly with time during pumping. Sludge samples were subsequently taken at the middle of each pumping period during the remainder of the investigation.

Soon after the introduction of alum to the No. 2 train of the plant, the sludge from No. 2 primary settling tank was observed to be of heavier consistency at the end of a normal period of pumping. Therefore, the pumping time from the No. 2 train was increased until the sludge being pumped at the end of the pumping period was of approximately the same consistency as that observed at the end of the pumping from the No. 1 train. The sludge volumes actually pumped from the two plant trains during each experimental period of this investigation, along with other pertinent sludge characteristics, are shown in Tables 35 and 36.

The data presented in Tables 35 and 36 indicate a decrease in sludge solids concentration on both trains beginning in Period 12. Various factors which might explain this decrease, e.g., sampling methods, analytical procedures, etc., have been investigated. However, no reasonable explanation for this apparent decrease has been found. The calculated grams (lb) of total solids or grams (lb) of volatile solids per million gallons of wastewater treated averaged about the same for both trains during the last seven weeks of the 37-week experimental program. As alum dosages and general levels of phosphorus and suspended solids removals on the No. 2 train did not decrease significantly during the last seven weeks, the sludge solids data for this period are suspect. Because of this, the summary of information presented in Table 37 does not include sludge solids data from the last seven weeks of the experimental program.

Table 37 indicates that on a unit treated flow basis, the total volume of sludge removed from the alum dosed train was approximately 32 percent greater, the pounds of total solids removed were about 28 percent greater, and the pounds of volatile solids removal were about 13 percent greater than from the undosed train. The decrease in percent volatile solids in the sludge from the alum dosed train was to be expected as the precipitated chemical sludge contributed non-volatile material.

TABLE 35

VOLUMES AND CHARACTERISTICS OF SLUDGES FROM TRAIN NO. 2 (ALUM)

Period	Dates	Total Solids %	Volatile Fraction %	Volume Pumped gpd	Volume Pumped gal/mil gal	Solids Pumped lb TS/mil gal	Solids Pumped lb VS/mil gal
1	1/25-2/13/72	4.4	66	8,250	5,770	2,120	1,400
2	2/15-2/25	3.1	72	8,950	6,100	1,580	1,140
3	2/26-3/8	4.0	68	8,708	6,300	2,100	1,430
4	3/9 -3/19	4.0	67	8,500	7,150	2,380	1,590
5	3/20-3/26	4.8	66	8,721	5,770	2,300	1,520
6	3/27-4/6	3.9	65	8,400	5,570	1,810	1,170
7	4/7 -4/20	3.8	67	8,210	5,330	1,690	1,130
8	4/26-5/25	3.8	66	9,113	6,510	2,060	1,360
9	6/3 -6/19	2.7	62	8,014	11,000*	2,470*	1,530*
10	6/24-7/11	2.5	65	5,243	11,630*	2,420*	1,500*
11	7/17-8/2	2.3	65	6,955	7,750	1,490	970
12	8/21-8/27	2.6	67	6,943	6,500	1,410	940
13	8/28-8/30	2.6	63	8,250	5,850	1,260	790
14	9/6 -9/11	2.2	65	7,516	6,380	1,170	760
15	9/12-9/17	2.3	66	8,250	6,110	1,170	770
16	9/18-9/21	2.3	59	8,250	5,610	1,080	640
17	{9/25-9/28 9/30-10/3	2.6	64	8,250	5,800	1,260	810
18	10/4-10/5	3.5	65	8,800	5,430	1,590	1,030

*Excessive pumping - not included in average amounts shown in Table 37.

Conversions: 1 gpd = 3.785 ℓ/day; 1 gal/mil gal = 0.001 ℓ/m^3; 1 lb/mil gal = 0.12 g/m^3

TABLE 36

VOLUMES AND CHARACTERISTICS OF SLUDGES FROM TRAIN NO. 1 (NO ALUM)

Period	Dates	Total Solids %	Volatile Fraction %	Volume Pumped gpd	Volume Pumped gal/mil gal	Solids Pumped lb TS/mil gal	Solids Pumped lb VS/mil gal
1	1/25-2/13/72	4.3	69	7,150	5,000	1,800	1,240
2	2/15-2/25	2.7	85	6,250	4,250	960	815
3	2/26-3/8	4.4	77	6,416	4,730	1,740	1,340
4	3/9 -3/19	4.0	79	6,500	5,450	1,820	1,440
5	3/20-3/26	3.6	78	6,521	4,310	1,300	1,010
6	3/27-4/6	4.2	78	6,600	4,370	1,530	1,190
7	4/7 -4/20	4.8	78	6,600	4,280	1,720	1,340
8	4/26-5/25	3.8	77	6,830	4,880	1,540	1,190
9	6/3 -6/19	4.1	71	6,521	4,460	1,530	1,090
10	6/24-7/11	3.1	78	7,761	4,320	1,120	875
11	7/17-8/2	3.3	66	6,988	5,170	1,430	950
12	8/21-8/27	2.7	75	6,118	5,760	1,300	970
13	8/28-8/30	2.7	74	6,600	4,680	1,050	775
14	9/6 -9/11	2.6	71	6,966	5,900	1,280	910
15	9/12-9/17	2.9	67	6,966	5,160	1,250	840
16	9/18-9/21	2.5	73	6,600	4,500	940	690
17	{ 9/25-9/28 9/30-10/3	3.1	66	6,700	4,720	1,220	805
18	10/4-10/5	2.8	70	6,700	4,130	970	680

Conversions: 1 gpd = 3.785 ℓ/day, 1 gal/mil gal = 0.001 ℓ/m^3,
1 lb/mil gal = 0.12 g/m^3

TABLE 37

SLUDGE PRODUCTION SUMMARY FOR 1/25/72 TO 8/27/72

	Train No. 2 (Alum)	Train No. 1 (No Alum)
Volume Pumped, gal/mil gal	6,275	4,748
Total Solids, %	3.57	3.85
Solids Pumped, lb TS/mil gal	1,894	1,483
Volatile Fraction, %	67	76
Solids Pumped, lb VS/mil gal	1,265	1,120

Conversions:
1 gal/mil gal = 0.001 ℓ/m^3
1 lb/mil gal = 0.12 g/m^3

Sludge Digestion

As described, the Chapel Hill plant employs anaerobic digestion as the first step in sludge disposal. Sludge is treated in a 22.9 m (75 ft) diameter primary digester with a 6.1 m (20 ft) water depth. Digested sludge is thickened and supernatant is separated in a 15.2 m (50 ft) diameter secondary digester. The primary digester is heated and maintained at about 95 °F and is equipped with a centrally located draft tube mixer which is seldom used. Mixing is normally accomplished with a 18.6 kW (25 hp) centrifugal pump which takes suction from the bottom of the digester and discharges into the center of the tank. This pump is operated for about one hour each day. The secondary digester is neither heated nor mixed.

The detention time in the primary digester, based on normal plant operation without alum addition, is about 48 days at a volumetric loading of 4.6 ℓ of sludge per m^3 (4600 gal sludge per mil gal) of wastewater treated. The normal volatile solids loading is about 0.62 kg/day/m^3 (0.039 lb/day/ft^3) of primary digester. Because of the relatively long digester detention time and the low volatile solids loading, no operating difficulties were anticipated with the digestion process during the alum addition program.

A summary of conditions in the primary digester during the course of the alum treatment investigation is given in Table 38.

TABLE 38

CONDITIONS IN PRIMARY DIGESTER DURING ALUM TREATMENT INVESTIGATION

Period	Volatile Acids mg/l	Alkalinity mg/l as $CaCO_3$	pH
1	230	2,069	7.0
2	101	2,516	7.1
3	110	2,736	7.1
4	103	2,817	7.1
5	94	2,850	7.3
6	94	2,873	6.9*
7	101	3,043	7.1
8	82	2,779	7.1
9	94	2,166	7.0
10	936	1,857	6.8**
11	132	2,350	7.1
12	141	1,588	6.9
13	158	1,531	6.9
14	51	1,641	6.9
15	73	1,806	6.9
16	123	1,449	6.9
17	292	1,517	6.8
18	384	1,384	6.8

* Sludge feed transferred to secondary digester.
** Lime added to primary digester.

During the first two months of operation with alum addition, no difficulties were experienced with the primary digester. All parameters remained within a range typical for digestion without alum addition. Late in March 1972 (Period 6), the pH dropped from above 7 to 6.9, and the methane content of the digester gas decreased from a normal level of about 68 percent to slightly less than 60 percent. It was suspected this might be due to inadequate mixing. Feed sludge was diverted to the 15.2 m (50 ft) secondary digester for several days, and the primary digester was given extra mixing. The primary digester recovered rapidly, and normal operation was resumed.

A similar condition developed in July 1972 (Period 10). In this instance, diversion of feed sludge to the secondary digester did not result in recovery of the primary digester. It was necessary to add 680 kg (1500 lb) of hydrated lime to the primary digester to raise the pH. As before, the methane content of the digester gas had decreased to about 60 percent and, prior to the addition of lime, the volatile acids increased from a normal level of 100 mg/l to over 900 mg/l. The addition of lime corrected the low pH, and the volatile acids concentration quickly returned to a typical low value. During the final two and one-half months of the alum treatment investigation (Periods 11 through 18), the alkalinity in the primary digester was about 1,000 mg/l less than normal (1,500 versus 2,500 mg/l), the pH tended to drift downward (7.1 to 6.8), volatile acids were gradually increasing (132 to 384 mg/l), and the methane content of the gas was less than usual.

The decreased detention time and the increased volatile solids loading might be suspected as causes of the difficulties with the primary digester. However, even with the additional sludge resulting from alum addition to one train, the detention time in the primary digester was decreased by only eight days to 40 days and the average volatile solids loading was increased by only 0.10 kg/day/m^3 (0.006 lb/day/ft^3) to 0.72 kg/day/m^3 (0.045 lb/day/ft^3). Both factors were still considered conservative for normal operation. Sulfide toxicity (via sulfate reduction) was also suspected, but the addition of 200 mg/l of alum to one plant train would result in a digester sulfide concentration of only about 16 mg/l, well below the concentration typically considered toxic. Whatever the cause of the problem with the primary digester, recovery was rapid after alum treatment was stopped in October 1972. Within two weeks, the pH increased to a value above 7, the alkalinity was back up above 2,000 mg/l, and volatile acids decreased to about 100 mg/l. On the basis of these results, it has been decided to provide convenient facilities for the addition of lime to the primary digester when permanent alum treatment facilities for dosing to both trains are constructed at the Chapel Hill plant.

In spite of the difficulty in maintaining a normal pH in the primary digester, the digestion process itself continued to produce a normal reduction in volatile solids throughout the entire alum treatment study. The volatile content of the mixture of digester influent sludges from the two plant trains averaged 70 percent. The average volatile fraction of centrifuged sludge was 50 percent. Assuming no change in fixed solids during digestion, these results indicate an average of 57 percent reduction in volatile solids in the digestion process. In fact, the volatile solids fraction in the centrifuged sludge averaged 47 percent during the final seven weeks of the investigation while the primary digester pH and alkalinity were trending down and the volatile acids concentration was rising.

Another problem was encountered several weeks after the start of alum treatment. Supernatant is decanted from the secondary digester continuously during the night hours. The total suspended solids concentration of the supernatant is generally less than 1,000 mg/l. About the end of February 1972 (Period 3), supernatant solids increased rapidly and remained high (8,000 to 20,000 mg/l) during the remainder of the experimental program. At the same time, the percent solids in the centrifuge feed, which is drawn from the bottom of the secondary digester, decreased from a normal range of 6 to 7 percent to an average of 3.8 percent. The sludge in the secondary digester did not thicken in a normal manner, nor was it possible to obtain a reasonable quality supernatant after the first month of alum treatment. The problem with heavy supernatant was particularly serious as the supernatant return line tended to clog quite rapidly after backflushing. On several occasions, it was necessary to discharge heavy supernatant to the undosed No. 1 train through a 15 cm (6 in) line at high rates, causing temporary upsets in the operation and performance of that train.

Because of the problems encountered in handling the mixture of alum humus and conventional primary sludges in the primary and secondary digesters, it has been recommended that a separate system for stabilization and disposal of alum humus sludge be included in any permanent alum treatment installation at Chapel Hill.

Sludge Dewatering

Two methods of sludge dewatering are available at the Chapel Hill plant. The method utilized routinely is the plant's solid-bowl centrifuge. The centrifuge is backstopped by 18 uncovered sand drying beds.

No difficulty was encountered in dewatering digested sludge with the centrifuge during the alum treatment program. It was, however, necessary to increase the operating time of the centrifuge because of the reduced solids concentration in the secondary digester underflow (the centrifuge feed). During normal plant operation without alum addition, the feed to the centrifuge averages between 6 and 7 percent solids and the digested solids can be dewatered with approximately 23 hours of centrifuge operation each week. Due to the increased volume of solids fed to the digesters and poor thickening in the secondary digester during the alum addition experiments, the volume of wet digested sludge to be dewatered increased about 70 percent, necessitating longer periods of time for centrifuge operation. Prolonged periods of centrifuge operation were not always possible as only one sludge hauling truck was available and the plant is not manned around the clock. It was frequently necessary to use the sand drying beds to accommodate the extra volume of sludge.

If alum had been added to both trains of the Chapel Hill Plant, the volume of digested sludge to be dewatered would have increased to approximately 2.4 times the conventional operation norm. Dewatering this volume of sludge would be impossible at the Chapel Hill plant without around the clock operation or the installation of additional dewatering equipment.

No problems were encountered in drying the digested sludge on the sand beds. The beds were filled to a depth of about 30 cm (12 in) and dried to a forkable consistency in periods ranging from three to six weeks during the late spring, summer, and early fall. The sludge dried with a whitish-gray surface crust which was apparently due to the various compounds of aluminum and phosphorus.

Chemical Costs

Liquid alum with an Al(III) content, by weight, of about 4.4 percent was used during this investigation. The chemical cost was $54.80 per equivalent ton of dry filter alum [$Al_2(SO_4)_3 \cdot 14.3\ H_2O$]. On the basis of a dosage of 175 mg/l of dry alum, the chemical cost per million gallons of wastewater treated was $41. Capital costs for permanent chemical storage and feeding equipment along with the requirement for additional maintenance and operator attention will add to the total cost. Additional sludge handling facilities, if needed, will also add to the total cost.

SECTION VI

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APPENDIX A

ABSTRACT OF PUBLICATION RESULTING FROM PROJECT

PHOSPHORUS IN WATER AND WASTEWATER - AN ANNOTATED SELECTED BIBLIOGRAPHY.
University of North Carolina, Chapel Hill. Wastewater Research Center.

Linda W. Little. Wastewater Research Center Report No. 11, November, 1970.
118 pp. FWQA Contract No. 14-15-505.

This volume comprises a selected annotated bibliography pertinent to sources of phosphorus in water and wastewater, effects of phosphorus on aquatic systems, behavior of phosphorus in soils and waters, phosphorus analysis, and removal of phosphorus from wastewater. Contains 281 entries.

APPENDIX B

ABSTRACT OF THESES RESULTING FROM PROJECT

ROBERT L. HANSON. Variations in Characteristics of Wastewater Influent at the Mason Farm Wastewater Treatment Plant, Chapel Hill, North Carolina. (Under the direction of JAMES C. LAMB III). Master's thesis submitted to the University of North Carolina in partial fulfillment of the requirement for the Master of Science in Sanitary Engineering, 1970.

Twelve composited samples of domestic wastewater influent were collected over two-hour intervals on each of seven different days, Sunday through Saturday, in July 1969 so diurnal variations in flow and constituent concentrations and loadings could be observed. The samples were analyzed for BOD, COD, TOC, nitrogen, phosphorus, MBAS, and specific solids and metal constituents. Influent flow was found to vary from 39 to 144 percent of average with the maximum flow between 1000-1200 hours and the minimum flow between 0400-0600 hours. The wastewater constituents showed a wide range of concentrations and loadings. Generally, the maximum concentrations and loadings occurred between 1000-1400 hours and the minimum values between 0600-0800 hours. The ratio of maximum to minimum concentrations for the constituents varied from 4-12 to one, while the same ratio for loadings varied from 10-40 to one.

GEORGE C. BUDD, JR. Laboratory Studies of Phosphate Removal by Addition of Lime to Wastewater. (Under the direction of JAMES C. LAMB III). Master's thesis submitted to the University of North Carolina in partial fulfillment of the requirement for the Master of Science in Environmental Engineering, 1971.

A study of pheromena associated with lime precipitation of phosphate in domestic wastewater, with observations based on the results of "jar tests" performed at the Chapel Hill Wastewater Treatment Plant. Effects of filtration, coagulation aid addition, fluoride addition, and hydroxyapatite addition were determined. On the basis of the results, it was concluded that additional phosphate reduction could be effected by filtration and coagulant aid addition. Neither fluoride addition nor hydroxyapatite addition had significant effects on phosphate removal.

THOMAS BATES. Phosphorus Removal from Trickling Filter Effluent Using Ferric Sulfate and Lime Precipitation. (Under the direction of LINDA W. LITTLE). Master's thesis submitted to the University of North Carolina in partial fulfillment of the requirement for the Master of Science in Public Health, May, 1973.

At the laboratory scale, phosphorus removal from trickling filter effluent was achieved by ferric sulfate-lime treatment. Four series of experiments were conducted to investigate the following parameters:

1. Comparison of the effectiveness of lime [$Ca(OH)_2$] with sodium hydroxide (NaOH) for pH control when used with iron (III) for phosphorus removal and control of residual iron.
2. Determination of the optimum pH for removal of phosphorus and elimination of effluent iron.
3. Effect, if any, of the order of addition of iron (III) and lime.
4. Comparison of the effectiveness of alum precipitation with iron-lime precipitation.

Based on the results obtained, the following conclusions were reached:

1. Lime proved more effective than sodium hydroxide when used with iron (III) for phosphorus removal and minimizing iron residual in the supernatant.
2. Optimum pH for iron-lime precipitation is approximately 7.5; iron (III) leakage can be minimized by pH control to above pH 7.
3. Iron (III) added pr[illegible] to lime addition produces a floc that is more compact and settles more rapidly.
4. Using pH control with lime, iron (III) compares favorably with aluminum (III) for phosphorus removal.

MARTIN STRAUSS. Effect of Colloidal Surface Area on the Removal of Phosphorus by Aluminum. (Under the direction of JAMES C. BROWN). Master's thesis submitted to the University of North Carolina in partial fulfillment of the requirement for the Master of Science in Environmental Engineering, 1973.

Effluents from trickling filters bear a substantial amount of colloidal particulates. Aluminum(III) added to such effluents for the purpose of phosphorus precipitation also coagulates colloids. Coagulation proceeds primarily as chemical sorption of a aluminum species onto colloidal surfaces. Colloidal surface area concentration is used as a parameter of aluminum(III) demand and its interference with phosphate removal is investigated in artificial systems containing phosphate and silica colloids.

Experiments showed that the range of particulate surface area in a trickling filter effluent is 50-100 m^2/l. Removal of 10 mg/l of phosphate as P is drastically impaired if colloidal silica is added to the phosphate solution at representative surface area concentrations. A linear relationship exists between aluminum(III) dosage required to remove phosphorus and initial colloidal surface area concentration. The effect of colloids on required aluminum(III) dosage is less pronounced at pH 6.0 than at pH 7.0. Additional aluminum(III) requirements for removal of phosphorus caused by colloidal silica surface area are due to competition of silica colloids with colloidal phosphate precipitates rather than with solution phase phosphate.

Inferences with respect to plant scale phosphorus removal are made. An experimental procedure feasible to investigate the effect of different size particulates on removal of phosphorus by aluminum(III) in trickling filter effluents is proposed.